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THE CYGNUS LOOP SUPERNova REMNANT:
NEW OBSERVATIONS AND A FRAMEWORK FOR UNDERSTANDING ITS
STRUCTURE AND EVOLUTION

by

JOHN JEFFREY HESTER

A THESIS SUBMITTED
IN PARTIAL FULFILLMENT OF THE
REQUIREMENTS FOR THE DEGREE

DOCTOR OF PHILOSOPHY

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HOUSTON, TEXAS
MAY, 1985
The Cygnus Loop Supernova Remnant: New Observations and a Framework for Understanding its Structure and Evolution

by

John Jeffrey Hester

Abstract

New observational data on the Cygnus Loop supernova remnant (SNR) include: (1) A detailed high resolution comparison of X-ray and optical emission for a field in the SE; (2) A map of the [O III] electron temperature for the field previously studied by Hester, Parker, and Dufour (1983); and (3) CCD imagery of the NE limb in the light of four emission lines. A wide range of new and existing observations of the Loop are for the first time interpreted within the context of a single physical description.

The Cygnus Loop is not an evaporative SNR evolving into the McKee and Ostriker (1977) ISM, nor are tiny cloudlets necessary to explain its morphology. The data show the Cygnus Loop to be evolving into a medium consisting primarily of an intercloud phase with \( n_0 \approx 0.1 \) cm\(^{-3}\) containing clouds with parsec dimensions and \( n_0 \lesssim 10 \) cm\(^{-3}\). The optical emission arises from extensive sheet-like radiative shock fronts driven into the clouds. These fronts locally form the outer boundary of the remnant. The appearance of X-ray emission outside the optical emission on the limbs is due solely to projection effects. The distorted and bumpy shock front is shown to give rise in projection to
the filamentary morphology of the remnant. Variations in spectral characteristics of the optical emission are due to a general increase in completeness of the recombination region and decrease in \( v_s \) with increasing distance away from the edge of a cloud along the face of the front. Models show that the sheet geometries needed to explain the shapes and extents of observed filaments lead to surface brightness and kinematic properties of the emission which are in very good agreement with observation. These geometries require density inhomogeneities within clouds of only \( \sim 10\% \) on scales of \( \sim 10^{17} \) cm. A thick (~ 2") recombination region, resulting from field limited compression, is resolved for the first time. The expected relationship between nonsteady flow and high [O III] electron temperature is confirmed.

Evaporation of clouds cannot account for the X-ray data. The brightest X-ray emission in the Loop comes just interior to young optical emission, and the gas has a pressure of at least six times the average for the Loop. Regions around clouds which should have undergone significant evaporation are not bright in X-rays. The X-ray data can be explained within the context of the large cloud picture by the combined effects of (1) a denser than average intercloud medium near clouds; (2) inertial pressurization of the X-ray emitting shell behind rapidly decelerating portions of the blast wave; and (3) strong compression of the hot gas by reflected and bow shocks around clouds.
ACKNOWLEDGEMENTS

The list of those to whom I owe a debt of gratitude is a long one, indeed, and any list that I compile will be woefully incomplete. To those who are left out, the omission is in my memory of the moment, and not in my appreciation for your friendship and assistance.

First and foremost, I would like to thank my family for the part they have played in my graduate career. My wife, Vicki, has put up with much over the years. She has willingly put her own career on hold, worked long and bizarre hours to support the family financially and allow me time to work, and shouldered more than her share of family responsibilities. She would have been justified many times over to insist that I quit and get a job, but has instead been an unending source of strength, encouragement, love, and perspective.

Vicki has also borne two beautiful daughters in the last five years. As I sit at my desk (and sometimes holler for quiet), Janice often asks me what I'm doing, and why I'm doing it. I try hard to explain, but have trouble doing so. She says that she wants to be a scientist when she grows up (at least when she's not being a ballerina), and shows remarkable patience with her crotchety old daddy. She may
retain memories of these years when she is older -- I hope so. Susan won't remember her first year, but I certainly will, and my memories will be fond ones.

I would like to thank my parents, Mr. and Mrs. Charles J. Hester, both for providing encouragement and financial assistance during my tenure as a student, and for other things too numerous to mention. I don't think that they have ever understood exactly what I am doing or why I am doing it, but they have made numerous sacrifices in order that I might have the opportunity.

I would like to thank William H.-M. Ku of the Columbia Astrophysics Lab for providing the X-ray data presented and for a preprint of the work of he and his collaborators on the Cygnus Loop. Richard Teske and Robert Kirshner made a copy of their work on the Fe coronal line emission from the Loop available in advance of publication. Roger Chevalier called my attention to the possible importance of thermal instabilities in radiative shocks. Thanks to John Dickel and William Straka for a copy of their VLA map of the NE limb of the Cygnus Loop and their ideas on its interpretation.

Special thanks go to John Raymond for critical reading of portions of this manuscript, and to he and his family for their hospitality during a visit to the Center for Astrophysics in December 1984. He made the suggestion that
the sheet model should be extended to cover kinematic observations, which lead me to develop the models described in Chapter 4. I would also like to acknowledge useful discussions with John, and thank him for accepting me as a collaborator in some of his research on the Cygnus Loop.

My appreciation for the advice, suggestions, encouragement, criticism, and friendship given me by Don Cox is great. As a sounding board for ideas, Don always returns more than is thrown at him, and I am a much better astrophysicist for what I have learned from him. Don's door was always open, especially during my advisor's sabbatical in 1983 and 1984.

I would like to thank my thesis advisor, Reginald J. Dufour. Reggie was willing to work with me and provided much needed encouragement during extended periods when due to personal reasons I was unable to really devote myself to research and studies. He allowed me to choose the course of my research and, despite the fact that his interests lie primarily in other directions, was a source of guidance and ideas throughout.

I have enjoyed working with Robert Parker for the last five years, as well. It was his data that got me into this game in the first place, and largely his continued interest (not to mention money) which kept me there. I would like to acknowledge his assistance, and thank him for his suggestions and ideas throughout the course of my research.
I have had a number of friends while a graduate student, and would like to thank them all. In particular, I would like to thank Rob Pennington for helping to make life interesting. Rob is both a good friend and a respected colleague. We have shared much, including lots of software, and more than a few beers.

Others whose friendship and assistance I would like to acknowledge include Peter Shull, who is a friend of many years. Thanks go also to Don Johnson and J. D. Wise of the Electrical Engineering Department for computer support. Mike Caplinger digitized the plates used in Chapter 3 and did the density to intensity conversion. He also played a part in the development of the image display software used. I'd like to thank the members of the Department of Space Physics and Astronomy as a whole both for the formal education I received here and for the climate and resources that made my research fruitful. Special thanks go to Umbe Cantu, who is an asset to the Department, and whom I consider a friend.

Financially, things have not been simple during my graduate career. Thanks go to Advanced Studies and Research and the Department of Space Physics for financial support. I would like to gratefully acknowledge very generous awards over the last three years from the Achievement Rewards for College Scientists Foundation, administered through the university, without which I would
not have been able to remain a student. I would also like to acknowledge a National Science Foundation Graduate Fellowship held during the middle three years of my graduate career. The research conducted was supported in part by NASA contracts NAS9-15940 and NAS9-16596. Support for travel also came from the National Optical Astronomy Observatories.
FOREWORD

The research in this thesis reflects scientific interests which arose from the research that I conducted for my Masters degree. Originally, I had intended to pursue a project of imagery of spiral galaxies for my dissertation research. (In fact, I made several observing trips to gather data for that project and spent a good deal of time on it. That project is not dead, and I hope to return to it in the not too distant future.) Eventually, however, my scientific interest in SNR research (not to mention trouble with the plate scanner) won out. In retrospect I'm not disappointed with the direction taken, and hope that the observations presented and conclusions drawn in this thesis represent a significant contribution to SNR research.

The organization of the material presented is somewhat choppy, and I would like to apologize for that fact. The only chapters of the thesis which were written as such are the introduction and Chapters 5 and 6. Chapters 2, 3, and 4 were written as drafts of papers intended for submission for journal publication. As a result, some repetition occurs between chapters in areas that are touched on by different papers. This is especially true of the introductions to each chapter. Unique information and different emphasis are
found in each, however, and I have opted to include them in the thesis intact. Chapter 2 (optical/X-ray comparisons) was written with Don Cox as a coauthor, and Don deserves much of the credit for the form of this work as presented. It has been submitted, received a favorable review, but will be rewritten before resubmission anyway. I hope that Chapters 3 and 4 will be ready for submission by the time that I leave Rice in July.

Papers are included in the thesis in the order in which they were written. This is not the most logical thesis organization possible. There is enough temporal evolution of ideas preserved in this order, however, that I decided to stay with it. Since each chapter can be read apart from the rest of the thesis, the reader may wish to skip around a bit. I will include here a quick tour of the terrain.

Chapters 2 and 4 contain most of the meat of the thesis. Chapter 2, which discusses the X-ray emission from the Loop, probably contains the most interesting physics, per se. Chapter 4 presents an overall picture of the Cygnus Loop, and discusses its applications to a large range of observations. Chapter 3, on the electron temperature inferred from [0 III] emission, presents a few neat results, and I think represents about the limit of what can be done quantitatively using photographic image tube plates. Chapter 5 is a quick look at new imagery data obtained using a state of the art solid state detector. Chapter 1 reviews
SNR evolution, observations of the Cygnus Loop, and the physics of radiative shock waves. Chapter 6 includes a very brief review of the high points of the research.

Before closing, I would like to note that much of my time at Rice University was spent developing software for image processing and display and for reduction of 1-D spectral data. This work will be described in a document to be completed this summer.
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There are no whole truths; all truths are half-truths.
It is trying to treat them as whole truths that plays the devil.

Alfred North Whitehead
(1861 - 1947)
CHAPTER 1

INTRODUCTION

I. Why?

Before bothering to review what is known about supernova remnants in general, or the Cygnus Loop in particular (and certainly before presenting any new research) it is reasonable to ask "who cares?" Apart from the availability of funds for the project (which is no mean reason, mind you), supernovae and supernova remnants are of considerable scientific interest.

One reason for interest in supernovae is that they are primarily responsible for the synthesis of a number of elements (e.g., oxygen and iron group nuclei) from hydrogen and helium, as well as the injection of these elements into the interstellar medium (ISM). Supernovae may be the largest source of primary cosmic rays. Observations of supernovae and their byproducts provide tests of our fundamental knowledge of nuclear, atomic, and particle physics, and enhance our understanding of the genesis of the stuff of which people (and by implication, dreams) are made.
Supernovae (which represent the most violent way in which stars meet their maker, so to speak) also liberate a tremendous amount of energy. They occur at a rate of only about 1 per 50 years per galaxy. This number seems rather small, especially considering the fact that a galaxy such as ours is composed of \( \sim 10^{11} \) stars, but each explosion results in the release of \( \sim 10^{49} \) ergs in the visual part of the spectrum alone. At its peak, a supernova may have an absolute visual magnitude of \(-19\), corresponding to a luminosity \(10^{10}\) times that of the sun, or comparable to the total luminosity of a medium sized galaxy. This brightness (and the fact that all supernovae of a given type seem to have about the same intrinsic luminosity) makes supernovae excellent choices as standard candles for use by observational cosmologists.

Despite the visible spectacle of a supernova explosion itself, the energy tied up in the optical flash represents only a very small part of the total energy released by the explosion. Most of the observable energy (i.e., energy in forms other than neutrinos) released by the explosion appears as kinetic energy of the ejecta. Supernovae eject up to about a solar mass of material at velocities of \(10^4\) km s\(^{-1}\), amounting to the release of \(\sim 10^{51}\) ergs into the surrounding medium. The release of this much energy once every 50 years or so appears to be adequate to dominate the dynamics and phases of the ISM, and may influence galaxy
formation and morphology and play a role in triggering the formation of new generations of stars.

The aftermath of a supernova explosion (i.e., the "supernova remnant," or SNR for short) is also an extraordinary physics laboratory. Among the topics available for study are problems in one, two, and three dimensional magnetohydrodynamics, strong collisionless shocks, plasma instabilities, time dependent nonequilibrium cooling of a hot plasma, numerous questions in atomic physics, formation and destruction of grains, and the production and confinement of relativistic particles. SNRs tend to radiate copiously at optical, UV, radio, and X-ray wavelengths, and will probably be found to be interesting infrared and gamma ray sources as well (when people get around to looking). Work on SNRs has implications for a variety of other astrophysical systems, including Herbig-Haro objects, Wolf-Rayet shells, accretion systems such as dwarf novae, and active galactic nuclei, to name but a few. The supernova blast wave is also a very good probe of the structure of the surrounding ISM. This is especially true since the goings on in and about SNRs may well be the dominant factor in determining what that structure is.

So far, so good -- SNRs are worth studying. Now what about the next question: "Of all known SNRs, why get so excited about the Cygnus Loop?" The answer lies with the fact that the Cygnus Loop is nearby and is relatively
unobscured by intervening material. As a result, the Cygnus Loop has become the prototype for middle aged SNRs. If you suspect that this also makes the Cygnus Loop a very well studied object, you are right. Despite all we know about it, however, our understanding of the Cygnus Loop is remarkably limited.

As noted in the Foreword to this thesis, most of what follows was prepared not as a thesis, per se, but rather as drafts of papers intended for submission to a professional journal. As such, it assumes that the reader has some degree of knowledge about SNRs in general, and the Cygnus Loop in particular. The rest of this introductory chapter will be devoted to laying such a foundation. Section II will review the observations of the Cygnus Loop. Since pertinent observations are normally outlined in context within each of the following chapters, this review will be especially brief. Section III will discuss the evolution of a SNR in a homogeneous medium. Section IV will treat the subject of radiative shocks. Section V will discuss issues which arise when the assumption of homogeneity is relaxed.

As I begin the project of trying to familiarize the reader with the background material required to make the rest of the thesis intelligible, I realize that to write a thorough review of all of the issues impinging upon the current work would require a year's time and merit a degree
in itself (and would almost certainly not be read by a single member of the committee!). As a result, I will try to touch on the highlights, and apologize to the specialist who may one day find a copy of this in his or her hands for the plethora of inaccuracies and omissions which will undoubtedly permeate the fruit of my labor.

I do hope, however, that this chapter might give a future graduate student or two a toe-hold in the basic literature which I had to carve (and am still carving!) for myself. To further assist these hypothetical individuals, I would like to mention that reviews of SNRs and related topics include those of Woltjer (1972) (SNRs), Chevalier (1977) (SNRs and their interaction with the ISM), McCray and Snow (1979) (ISM), McKee and Hollenbach (1980) (shock waves), Holt (1983) (X-ray spectra of SNRs), and Raymond (1984) (observations of SNRs). The rest of this chapter draws heavily on these sources.

II. Observations of the Cygnus Loop

Optically, the Cygnus Loop (a.k.a. the Veil Nebula, the Network Nebula, NGC 6960, 6979, 6992/5) is a patchy ring of emission line nebulosity, about 3° in diameter, located in the constellation of Cygnus. Minkowski (1958) found that the bright filaments across the face of the Loop are expanding with an average velocity of 116 km s⁻¹. When
combined with Hubble's (1937) measurements of proper motion of filaments on the edge of the Loop, this yields a distance of 770 pc. At this distance, the 3° diameter corresponds to a size of ~ 40 pc, at a scale of 0.037 pc = 1.15 × 10^{16} cm per second of arc. Although serious questions exist about the validity of the procedure used to arrive at this result (e.g., Kirshner and Taylor 1976), various indirect measures of the distance (e.g., use of the empirical "Σ-R" relation between surface brightness and diameter, the low reddening, and the inferred explosion energy of ≤ 10^{51} ergs) suggest that the true distance is not much different from the canonical value.

Aside from the optical nebulosity, the Cygnus Loop is also a strong source of soft X-ray emission (e.g., Grader et al. 1970; Gorenstein et al. 1971; Stevens and Garmire 1973). Two dimensional X-ray images of the Cygnus Loop have been obtained by Rappaport et al. (1979) and Tuohy, Nousek, and Garmire (1979), and most recently by Ku et al. (1984). Ku et al. used both the image proportional counter and high resolution imager aboard the Einstein Observatory to map the entire Loop at a resolution of 1', and portions of the Loop at a resolution of ~ 10". The X-ray observations show a limb brightened shell structure, proving conclusively that the Loop is a single object. The detection of optical [Fe X] and [Fe XIV] line emission (Woodgate et al. 1977; Lucke et al. 1980) and evidence of subkilovolt oxygen and
iron line emission (Inoue et al. 1980; Kahn et al. 1980) confirm a thermal origin for the X-rays. The inferred temperature inside the Loop (~ 2 - 3 X 10^6 K) and the total brightness are consistent with a 400 km s^{-1} blast wave propagating into a medium with a preshock density of ~ .2 cm^{-3} (Tucker 1971; Ku et al. 1984).

At high frequencies, the radio spectrum of the Loop is a power law with a spectral index of ~ -.5 (DeNoyer 1974). Radio maps of the Loop (e.g., Colla et al. 1971; Moffat 1971; Keen et al. 1973; Dickel and Willis 1980) show a broken shell structure which closely correlates with the optical emission. A high resolution (but low signal to noise) map obtained with the VLA by Straka et al. (1985) shows detailed 1:1 correlations between radio and optical filaments. The emission is presumably due to synchrotron emission from regions where the magnetic field and ambient relativistic particle population have been compressed along with the thermal plasma behind radiative shocks.

A number of authors have studied the optical emission from the Cygnus Loop spectroscopically (e.g., Osterbrock 1958; Parker 1964a, b, 1967, 1969; Miller 1974). The most recent and thorough study is that of Fesen, Blair, and Kirshner (1982). Parker (1967) determined an average reddening for the Cygnus Loop of E(B-V) = 0.08 magnitudes. This number has since been treated as a canonical value, although Fesen, Blair, and Kirshner found variations of ~
.05 - .10 mag. Comparison of optical line strengths with model calculations of radiative shocks (e.g., Cox 1972a; Raymond 1979) have typically yielded shock velocities of ~ 100 km s\(^{-1}\) and preshock densities in the range of 2 - 10 cm\(^{-3}\), although certain lines (most notably [O III]) occasionally have strengths which cannot be accommodated by the models.

Kirshner and Taylor (1976) present Fabrey-Perot observations of faint high velocity H\(\alpha\) emission across the face of the Loop. Shull et al. (1982) used high resolution spectroscopy to study the kinematic structure of the gas.

Various imagery studies (e.g., Chamberlain 1953; Parker 1973; Gull, Parker, and Kirshner 1977; Fesen, Blair, and Kirshner 1982) have shown that the appearance of the Loop changes when viewed in the light of different emission lines. Hester, Parker, and Dufour (1983) effectively combined the techniques of imagery and spectrophotometry by using calibrated narrow-band imagery in the light of emission lines from six different ionic species to explore the two dimensional spatial structure of spectral line ratios.

Ultraviolet spectra have been obtained of optically bright filaments in the Cygnus Loop using the International Ultraviolet Explorer (IUE) by Benvenuti, D’Odorico, and Dopita (1978), Benvenuti, Dopita, and D’Odorico (1980) and Raymond et al. (1980a, 1981). UV spectra are interesting
because they reveal lines from hotter species than are available at optical wavelengths (C IV, N V, and O V) and the Mg, Si, and C lines provide information on the fate of grains in the hot medium behind the shock. These studies typically yield shock velocities (\(\sim 130 \text{ km s}^{-1}\)) which are somewhat higher than average for the optical determinations.

Optical spectra (Raymond et al. 1980b; Fesen, Blair, and Kirshner 1982; Treffers 1981) and IUE observations (Raymond et al. 1983) of a faint Balmer-line filament in the NE Cygnus Loop show the filament to be a collisionless shock with a velocity of \(\sim 200 \text{ km s}^{-1}\). The filament is coincident with the outer edge of the X-ray shell, and lies \(\sim 5'\) to \(10'\) beyond the bright optical filaments.

III. Evolution of a Supernova Remnant in a Homogeneous Medium

The evolution of a SNR in a homogeneous ambient medium has been treated by several authors. The evolution can be roughly split into four phases (e.g., Spitzer 1968; Woltjer 1972). Even though we will later decide that the assumption of homogeneity is inappropriate, these phases still provide both meaningful physical insight into real SNRs and a framework in which to understand them. Particular attention will be given to phases II and III, which are of particular importance when discussing the Cygnus Loop.
A. Phase I: Free Expansion

In phase I, the mass of the material ejected from the supernova is much greater than the mass of the swept-up ISM, so the evolution of the remnant is determined by the more or less unimpeded expansion of the ejecta, travelling at ~10,000 km s$^{-1}$ away from the site of the explosion. The term "free expansion" is actually a misnomer. The swept-up ISM does slightly decelerate the ejected material, and the large difference in velocity between the ejecta and the ambient medium results in reverse shocks being driven into the ejecta. The ejecta is also subject to Rayleigh-Taylor instability, and may further fragment during this phase. A better term for phase I is the "ejecta dominated" phase.

Observationally, these young objects are very exciting (e.g., filaments consisting of almost pure oxygen, an optical synchrotron nebula powered by a central pulsar, enormous proper motions of filaments, etc. ad infinitum), and conferences and symposia are frequently held in their honor. The best studied examples are Cas A and the Crab Nebula.

B. Phase II: Adiabatic Phase

After the supernova ejecta has swept up a few times its own mass in ambient material, the ejecta becomes dynamically
unimportant. The shell of the remnant is dominated by the swept up material, and the evolution of the remnant is better approximated by an expanding blast wave. In this stage the shock is very fast and the material behind the shock is heated to temperatures in excess of $10^6$ K. At such high temperatures, the plasma inside the blast wave is highly ionized. The species present have no low lying states which can provide efficient cooling by collisionally excited line radiation, and hence radiative energy losses are unimportant. Thus, in phase II the thermal and kinetic energy of the remnant are approximately conserved (hence the name "adiabatic"). Calculations of the X-ray emissivity of a hot plasma (e.g., Raymond and Smith 1977) indicate that the spectrum of adiabatic SNRs should be dominated by line emission from Fe XVII and hydrogenic and helium-like ions of oxygen, carbon, and nitrogen for internal temperatures below about $5 \times 10^6$ K, and by bremsstrahlung emission at higher temperatures.

Since the pressure inside the blast wave is much greater than the ambient pressure in the ISM, the blast wave can be assumed to be in the strong shock limit. Ignoring magnetic fields for the moment, the jump conditions for a strong shock (derived from the standard equations for conservation of mass, energy, and momentum across the shock) are:
\[
\begin{align*}
\rho &= 4\rho_0, \\
\rho &= \frac{3}{4} \rho_0 v_s^2, \\
T &= \frac{3}{16} \frac{m}{k} v_s^2 = 1.45 \times 10^5 v_7^2, \\
\text{and} \quad kT &= 1.25 \times 10^{-2} v_7^2 \text{ keV},
\end{align*}
\]

where the subscript 0 refers to conditions in front of the shock. The quantity \(v_7\) is the shock velocity in units of 100 km s\(^{-1}\). The quantity \(\bar{m}\) is the average particle mass behind the shock, including electrons. The numerical results assume 65\% H and 35\% He by mass, with complete ionization.

The assumption that the magnetic pressure can be ignored must be justified. The typical strength of the Galactic magnetic field is \(\sim 3 \mu\text{G}\). Assuming a "worst case" in which the field is parallel to the shock, the field will jump by a factor of 4, and the magnetic pressure is \(B^2/8\pi < 6 \times 10^{-12} \text{ dynes cm}^{-2}\). For \(n_0 = 0.2 \text{ cm}^{-3}\) and \(v_s = 400 \text{ km s}^{-1}\) and a medium which is 12\% He by number (typical values inferred for the Cygnus Loop from X-ray data) the thermal pressure is \(5.45 \times 10^{-10} \text{ dynes cm}^{-2}\), so the magnetic pressure does not affect the jump conditions.

The profile of the pressure, density, and temperature interior to the blast wave is given by a similarity solution first obtained by Sedov (1959). In this solution, the pressure at the blast wave is three times the central pressure. The density decreases sharply and the temperature
rises toward the center of the the expanding cavity, leading to a very hot, rarefied interior. Almost all of the swept-up mass is found in an outer shell with thickness $1/12$ $R$ (where $R$ is the radius of the remnant). The size of the remnant and the velocity of the blast wave are given by

$$R = 1.17 \left( \frac{E_0}{P_0} \right)^{1/5} t^{2/5}$$

and

$$v_s = \frac{2}{5} \frac{R}{t}.$$

Most of the shell of the Cygnus Loop appears to be an adiabatic blast wave (e.g., a limb brightened soft X-ray shell without optical emission). Setting $v_s = 400$ km s$^{-1}$ and $R = 20$ pc immediately yields an age for the Loop of $t = 20,000$ years.

Similarity solutions such as those of Sedov have recently been discussed by Cox and Franco (1981), Cox and Edgar (1983), and Edgar and Cox (1984) for cases where the explosion occurs in a pre-existing cavity with $p_0 = R^\alpha$ Thermal conduction by the hot electrons has the effect of smoothing out the temperature and density profiles in the interior of the blast wave (Chevalier 1975; Solinger, Rappaport, and Buff 1975). Saying that the blast wave is "adiabatic" implies that radiative cooling is unimportant dynamically, but does not imply that the shock does not radiate at optical wavelengths. Chevalier and Raymond (1978) and Chevalier, Kirshner, and Raymond (1980) show that
detectable collisionally excited Balmer line emission can arise behind a collisionless shock propagating into a partially neutral medium. (As noted above, this has also been observed in the Cygnus Loop.)

C. Phase III: Radiative or Snowplow Phase

Eventually the radiative energy losses from the remnant will amount to a significant fraction of its initial energy, and the assumption that \( PV = \) constant will no longer be valid. It turns out that another way of stating this is to say that eventually the shock velocity will drop to the point where the cooling time of the gas behind the shock is short compared to the age of the remnant.

The cooling rate of a hot plasma can be written as

\[
L = \Lambda n_e n_p \text{ ergs cm}^{-3} \text{ s}^{-1}
\]

where \( \Lambda \) is a function of the temperature, composition, and past history of the plasma. Calculations of ionization equilibrium and radiative cooling which can be used to evaluate \( \Lambda \) for various parameters have been made by a number of authors, including Cox and Tucker (1969), Raymond, Cox, and Smith (1976), and Raymond and Smith (1977).

The time scale for radiative cooling of a parcel of gas, \( \tau_{\text{cool}} \), is given by

\[
\tau_{\text{cool}} = \frac{3}{2nkT} \frac{1}{\Lambda n_e n_p}.
\]
Assuming a constant shock velocity, $T$ is constant behind the shock, and $\tau_{\text{cool}} \propto n^{-1}$. For a 100 km s$^{-1}$ shock, the cooling times are given by $700/n_0$ years to cool enough for significant emission from [O III], and $2000/n_0$ years to cool enough to see emission from [S II] (Raymond et al. 1980a).

The cooling function from Cox and Tucker (1969) can be approximated as $\Lambda \propto T^{-1}$ in the range $10^5 \, K < T < 5 \times 10^6 \, K$. Assuming that the pressure driving the shock is constant, $n = 1/T$, so $\Lambda \propto n$ and $L \propto n^3$. In this case,

$$\tau_{\text{cool}} = \frac{P}{L} \propto n^{-3} \propto v^6.$$  

The dependence can actually be steeper than this. Behind the shock wave $p$ is approximately constant, so as $T$ decreases, $n$ increases, and the cooling rate increases as $n^3$. This is an unstable situation. The cooler a parcel of gas gets, the quicker it cools. Thus, as soon as the gas reaches some characteristic temperature ($\sim 5 \times 10^5 \, K$, corresponding to a 200 km s$^{-1}$ shock) it cools very quickly. (Compare the time scales for cooling behind a 100 km s$^{-1}$ shock given above with the age of the Cygnus Loop.) The details of this process make up the rather involved subject of the theory of radiative shocks, which will be discussed below.

We were talking about the radiative phase of a SNR. When material behind the shock starts to radiate efficiently, it is able to dump its thermal energy very
quickly, and the shock wave and cooling region behind it look something like an "isothermal" (i.e., $\gamma = 1$) shock. The remnant is no longer adiabatic. Rather, it is a dense shell (up to about 100 times denser than the preshock medium) expanding into and sweeping up the surrounding medium much in the manner of a snowplow. Its future evolution is governed primarily by momentum conservation in the shell. The condition

$$\frac{4}{3} \pi R^3 \dot{\rho} R = \text{constant}$$

can be integrated immediately to give $R = t^{1/4} + C$. The detailed understanding of this phase is due to Cox (1972b), who also applied this model to the Cygnus Loop (Cox 1972c).

D. Phase IV: An Identity Crisis

Before beginning discussions of radiative shocks or SNR evolution in an inhomogeneous medium, the end of the story of the shell should be told. Eventually the velocity of the shock drops to ~ 10 km s$^{-1}$, which is comparable to the random motions of clouds in the ISM, and the shell breaks up and loses its identity. Various estimates find that between 3% and 10% of the initial kinetic energy of the SNR will end up in kinetic energy of clouds (e.g., Spitzer 1968; Chevalier 1974; Salpeter 1976). This energy input seems
about right to maintain the observed kinetic energy of Interstellar clouds (e.g., Siluk and Silk 1974).

IV. Radiative Shocks

An excellent and comprehensive (if somewhat dense) review of interstellar shocks can be found in McKee and Hollenbach (1980). This section will concentrate on a basic understanding of radiative shocks such as those found in older SNRs.

A. Steady Flow Shocks

1) Basic Physics

The discussion in Section III.C of how cooling "turns on" lays the groundwork for understanding radiative shocks. The shock wave heats and ionizes the preshock gas, and compresses it by a factor of 4. As the material cools, its density rises, and as its density rises, it cools faster. The net result of this is that cooling and recombination of the gas is essentially a critical phenomenon, which happens quite suddenly.

Figure 1 shows a schematic drawing of the cooling and recombination region behind a shock with a velocity of about 100 km s\(^{-1}\). Emission from "hot" lines such as N V, O IV],
C IV, and [O III] come from the "cooling region" immediately behind the shock. In this zone the temperature falls from \( \sim 2 \times 10^5 \) K to \( \sim 30,000 \) K. Balmer lines of hydrogen and forbidden lines such as [N II] come from the "recombination zone". (Emission from [O II] is interesting because it comes primarily from the hot end of the recombination zone, and so is intermediate between [O III] and Hα.) "Cool" lines such as [S II] and [O I] come from the trailing side of the recombination region. The nature of this cooling and recombining flow makes the cool lines much stronger in the spectrum of a radiative shock than in the spectrum of an H II region, where the ionization balance is such that few atoms are in these low ionization states.

Cox (1972a) was the first to calculate the structure of the cooling and recombining flow behind a shock with a velocity of \( \sim 100 \) km s\(^{-1}\). He assumed that the flow was laminar, that the shock was plane parallel, and that the column density through the shock was large enough for the cooling and recombination region to have completely formed. (These assumptions jointly define what is meant by a "steady flow" shock.) He found that the basic picture described above must be modified to include heating of the recombination zone by UV photons (e.g., He II Ly \( \alpha \lambda 304 \)) produced in the hot part of the flow. A typical H atom is photoionized and recombines several times before completing its passage through the recombination zone.
Cox also put a physical scale on diagrams such as Figure 1. According to his (and subsequent) calculations, the entire thickness of the cooling and recombination region is \(\lesssim 10^{16}\) cm, or \(<1"\) at the distance of the Cygnus Loop. Thus, if the observed emission arises from radiative shocks such as these, all of the action occurs on scales below the resolution of ground based telescopes. What is observed is the integrated spectrum of the entire region.

The affect of magnetic fields must again be addressed when discussing radiative shocks. Assuming \(B_0 = 3\mu G\) (tangential to the shock front), \(v_s = 100\) km s\(^{-1}\), and \(n_0 = 10\) cm\(^{-3}\), the thermal pressure behind the shock is \(\sim 1.7 \times 10^{-9}\) dynes cm\(^{-2}\) (\(~\) constant) and the magnetic pressure is \(\sim 3.6 \times 10^{-13}\) \((n/n_0)^2\). The magnetic pressure will stop further compression when it becomes equal to the thermal pressure. This occurs for \(n/n_0 \approx 70\), or \(n = 700\) cm\(^{-3}\) using the stated parameters. If this happens then much of the final cooling must occur at a lower density than previously calculated, and the trailing part of the recombination zone will be strung out over a much larger distance.

ii) More Models

The spectrum of a radiative shock is sensitive to a variety of parameters. These include the preshock density, the shock velocity, the chemical composition of the gas, the
tangential component of the magnetic field, the ionization state of the preshock gas, and \( R_{\text{max}} \equiv 4\pi J_\|/F_\| \) -- a measure primarily of the geometry of the shock front). Much work has been done in the field since the early models. Dopita (1976, 1977) primarily varied metal abundances to test their effect (although his models neglect He II \( \lambda 304 \) cooling). Raymond (1976, 1979) improved on the treatment of Cox by allowing specification of the preshock ionization balance as an initial condition, and presented an extensive grid of model calculations. Butler and Raymond (1980) added the effects of charge exchange reactions to the calculation. Shull and McKee (1979), who also improved on the atomic physics of early models, attempted to remove the preshock ionization as a free parameter by treating it self-consistently with the UV precursor of the shock. This assumption is not universally applicable, however. Cox (1982, private communication) has pointed out that the recombination time of the gas in front of the shock is long enough that it will "remember" a high ionization state for times that are long compared to the time scale for a change in \( v_\| \). Raymond and Blair (1985) have pointed out that a shock which has only recently encountered a dense region will not have produced enough UV photons to preionize the medium.

Cox and Raymond (1984) have introduced the concept of preionization-dependent "families" of shocks. They suggest
that the main difference between a 140 km s$^{-1}$ shock propagating into a neutral medium and a 119 km s$^{-1}$ shock propagating into a fully ionized medium, for example, is that the fast shock shock into the neutral medium must provide the energy to initially ionize the gas. Downstream of the ionization zone the enthalpy per particle is the same in both cases, and the rest of the evolution of the flow is very similar.

iii) Radio Emission from Radiative Shocks

The mechanism by which radiative shocks produce synchrotron radiation was first discussed by van der Laan (1962a), and later by Duin and van der Laan (1975). While this topic is tangential to the research presented in the thesis, it is central to an ongoing project. As no clear derivation of the result appears in the literature, one will be included here.

Assuming a local ambient flux of relativistic electrons of the form

$$N(E)dE = K_0 E^{-\gamma}dE$$

and a local magnetic field strength $B_0$, the volume emissivity of synchrotron radiation at a frequency $\nu$ is given by

$$\varepsilon_0(\nu) = CK_0 B_0^{1-\alpha} \nu^\alpha$$
where $\alpha \equiv -(\gamma - 1)/2$ is the spectral index of the emission. If the emission is arising in the presence of thermal electrons, then the emissivity will be suppressed for frequencies less than a critical frequency, called the Razin frequency (see Lang 1978), which depends on the density of thermal electrons and the strength of the field.

Ignoring the complication of the thermal plasma (which doesn't affect frequencies above a few MHz for parameters applicable to the Cygnus Loop) the high compression which occurs in the recombination zone behind a radiative shock has two effects. First, as the thermal particles are compressed they drag the field with them. For compression perpendicular to the field, $B \propto n$. Second, the ambient population of relativistic electrons act to conserve the flux enclosed by their orbits ($m^2 \gamma B = \text{the first adiabatic invariant}$) which implies that they are both compressed and accelerated by the changing field. Assuming all of the momentum of the electrons is perpendicular to $B$, $p^2/B$ = constant. For ultrarelativistic electrons, $E = cp \propto n^{1/2}$. The shape of the power law spectrum is not changed by this acceleration, but electrons move up the spectrum in energy.

The net effect on the particle population can be calculated by assuming that all of the electrons in volume $V_0$ with energy in the range $E_0 + \Delta E_0$ before compression end up in volume $V_2$ with energy in the range $E_2 + \Delta E_2$ after compression:
\[ \int_{V_0} dV \int_{E_0}^{E_0+\Delta E_0} K_0 E^{-\gamma} dE = \int_{V_2} dV \int_{E_2}^{E_2+\Delta E_2} K_2 E^{-\gamma} dE. \]

Using \( V_2/V_0 = n_0/n_2 \) gives

\[ \frac{K_2}{K_0} = \frac{n_2}{n_0} \frac{E^{-\gamma+1}}{E_0^{\gamma+1}} \frac{E_0+\Delta E_0}{E_0} \frac{E_2^{\gamma+1}}{E_2^{\gamma+1}} \frac{\Delta E_0}{\Delta E_2} \]

In the limit \( \Delta E_0, \Delta E_2 \to 0 \), \( (\Delta E_2/\Delta E_0) = (n_2/n_0)^{1/2} \), giving

\[ \frac{K_2}{K_0} = \left( \frac{n_2}{n_0} \right)^{(\gamma+1)/2} \]

which recovers the formula given by Duin and van der Laan.

Substitution of this relationship and \( B_2/B_0 = n_2/n_0 \) into the expression for the volume emissivity then yields directly

\[ \varepsilon(\nu) = \varepsilon(\nu') \left( \frac{n_2}{n_0} \right)^{\alpha} \left( \frac{\nu}{\nu'} \right)^{\nu+1}. \]

The spectrum of the Cygnus Loop has \( \alpha = -0.5 \) (DeNoyer 1974), which implies \( \gamma = 2 \). Thus adiabatic compression of the magnetic field and the ambient population of relativistic particles in the cooling region will result in an increase in the synchrotron volume emissivity of the gas which is proportional to \( n^3 \).
B. Deviations from Steady Flow

The first observational evidence for nonsteady flow in the Cygnus Loop can be found in the spectrophotometry of Miller (1974). For his position 3, \([\text{O III}] \lambda5007/\text{H}\beta = 9.5\), substantially higher than the peak value of \(~6\) obtained from model calculations. Since that time numerous examples of positions with exceptionally strong \([\text{O III}]\) have been found (e.g., Fesen, Blair, and Kirshner 1982; Hester, Parker, and Dufour 1983). Raymond et al. (1980a, 1981) suggested that these discrepancies are likely due to departures from steady flow behind the shock, and that suggestion is now accepted by essentially all workers in the field. There is, however, no general agreement on the nature or cause of the nonsteady flow.

1) Small Cloudlets

Raymond et al. (1981) suggested that one way to achieve nonsteady flow is for the medium to be composed of cloudblets which are too small to allow the entire cooling region to form (i.e., have column depths which are smaller than the column depths through a steady flow model of a radiative shock). Fesen, Blair, and Kirshner (1982) picked up on this idea and ran with it. They suggested that the preshock medium was composed of myriads of tiny (in fact unresolved)
cloudlets, so that shocks probably never get a chance to form complete cooling and recombination regions. They applied this scenario to other problems, as well, such as the observed stratification of the emission when viewed in the light of different emission lines. The fact that the observed emission is filamentary required them to suppose that the tiny cloudlets came prepackaged in brick-like structures which are swept up to form the observed filaments. This basic picture has since been applied to other observations such as the X-ray and coronal line emission from the Loop. (It will be discussed at some length and eventually discarded in Chapter 2.)

11) Recent Encounters with Large Clouds

It takes time for a shock to sweep up enough material for a complete cooling and recombination region to form. The flow behind a shock front working into the outer parts of a large cloud will take as much as $\sim 10^3$ years to fully develop. Very early in its evolution, such a shock will only show emission which originates in the cooling zone (e.g., optical emission from [O III] and UV lines of O III, C IV, and N V). When the recombination region begins to form, emission from [O II] will be seen, followed in time by emission from species found in progressively cooler parts of the flow (e.g., Hα, [S II], and [O I]).
Hester, Parker, and Dufour (1983) found that filaments could be classified into types on the basis of the lines in which they appear. Type I features are present in all observed lines, as is characteristic of complete recombination regions. Type 1.5 features are absent (or at least very weak) in the coolest lines such as [O II] and [S II], but present in [O III] and [O II]. Type II features are strong only in emission from [O III] and lines from other high ionization potential species.

The association of feature types II, 1.5, and I with shocks having increasingly more complete recombination regions is obvious. The picture is made even nicer by the observation that in the SE a transition takes place from type II → type 1.5 → type I features with increasing distance behind the leading edge of the emission. The scale for this transition is explained by the distance the blast wave travels ahead of the projected position of the radiative shock in a cooling time. Hester, Parker, and Dufour found that features judged to be type I on the basis of their morphology in different lines agreed fairly well with the results of model calculations.

iii) Thermal Instabilities

A final class of mechanisms whereby the assumptions of steady flow may be invalidated involve thermal instabilities
in the cooling flow. As discussed above, a denser parcel of
gas will cool faster, become denser, and cool faster yet.
It has been suggested that this could result in unstable
collapse of portions of the flow. An approximate condition
for the onset of such instabilities was given by Field
(1965) as $S = d(\log \Lambda)/d(\log T) < 2$.

Thermal conduction will damp disturbances with short
wavelengths. The fact that conduction is inhibited across
field lines, however, lead McCray, Stein, and Schwarz (1972)
and Duin and van der Laan (1975) to suggest that the gas
will collapse into thin filaments aligned along field lines.
Smith and Dickel (1983) calculate the fate of thermally
unstable filaments behind a shock, and find that they
flatten into sheets.

McCray, Stein, and Kafatos (1975) and Chevalier and
Imamura (1982) treat instabilities which do not violate the
assumption of planar flow (i.e., instabilities which cause
the cooling and recombination regions to break up into a
series of thin sheets). McCray, Stein, and Kafatos
considered a shock moving into a region of sinusoidally
varying density and find that the density inhomogeneities
are amplified in the flow behind the shock. Chevalier and
Imamura investigate oscillatory instabilities in the flow,
assuming that a piston is being driven into a gas at
constant velocity (much like the "snowplow" of a SNR in the
radiative phase). They find that the flow is unstable if $S$
< 0.4 (for the fundamental mode) or S < 0.8 (for the first and second overtones). A geometrical instability arising from focussing of material behind the shock has been discussed by Chevalier and Theys (1975). This instability, which is related to the Rayleigh-Taylor instability, arises when a slightly denser region is encountered by a radiative shock that is being driven primarily by the inertia of the material immediately behind it.

None of these calculations simultaneously consider effects such as thermal conduction, time dependent cooling, the affect of magnetic pressure, or radiative coupling between the various zones in the cooling and recombining flow. They do, however, suggest that the assumption of laminar flow might not be valid in some cases. Imagery studies such as those in the current work might be ideally suited for finding evidence of such instabilities.

V. SNRs in an Inhomogeneous Medium

The discussion in Section II assumed that the medium around the site of the supernova was homogeneous and isotropic. The real ISM falls far short of satisfying these constraints. A large number of techniques reveal the presence of a variety of phases in the ISM including dense molecular clouds (T ~ 10 K, n_e ~ 10^2 cm^{-3}), diffuse clouds (T ~ 10^2, n_e ~ 10 cm^{-3}), a warm intercloud component (T ~
$10^4 \text{ K}, \, n_e \sim .1$), and a coronal phase ($T \sim 10^{5-6} \text{ K}, \, n_e \sim 10^{-3} \text{ cm}^{-3}$). The evolution of SNRs is potentially very different depending upon the details of the structure of the medium into which they evolve.

Cox and Smith (1974) noted that the energy input of supernovae into the ISM is adequate to maintain a network of tunnels of coronal gas in the ISM. Their argument is straightforward: Given the observed rate of supernovae, the volume of galactic disk, the rate at which SNRs expand, and the lifetime of the hot gas, the hot interiors of SNRs will often overlap. McKee and Ostriker (1977) proposed a model for the ISM in which the coronal gas has a very large filling factor, and in fact provides a matrix in which are embedded disconnected pieces of the denser, cooler phases. A detailed model of SNR evolution in such a medium has been developed by Cowie, McKee, and Ostriker (1981). In their view, the SNR evolves primarily in the hot low density phase. Radiative shocks driven into denser clouds encountered by the blast wave give rise to optical emission. The clouds are quickly engulfed by the blast wave, and find themselves surrounded by very hot gas in the interior of the remnant. There, thermal conduction at the interface between a cloud and the hot medium causes the cloud to evaporate. Since conduction is proportional to $T^{5/2}$, this process will tend to be more important in the early parts of the adiabatic phase of evolution. SNRs are considered to cool
at about the time they overlap, and so form the next
generation of clouds. The time scale for exchange of
material between the hot phase and the various cloud phases
in this model is \( \sim 10^6 \) years.

The idea of SNR evolution in an inhomogeneous medium
explains many observations not easily accounted for in the
earlier models. For example, the discrepancy between shock
velocities inferred from X-ray data and those inferred from
optical data is easily explained by the presence of a wide
range of preshock densities. In addition, models such as
that of Cowie, McKee, and Ostriker directly couple the
evolution of SNRs with the structure and dynamics of the
ISM. Observations of SNRs yield information about the
medium into which they propagate, which may or may not look
like the McKee and Ostriker ISM. The physical processes
which dominate the evolution of SNRs in the Cowie, McKee,
and Ostriker model (e.g., thermal evaporation of clouds) can
be studied directly in SNRs. (Later in this thesis --
primarily in Chapter 2 -- it will become evident that the
Cygnus Loop is not the standard evaporative remnant
described in their model.)
FIGURE CAPTIONS

Figure 1.1. A schematic diagram of the structure of the cooling and recombinating flow behind a radiative shock front with velocity $\geq 100$ km s$^{-1}$. The horizontal axis is distance behind the shock front, with the shock front itself located at the left side of the figure. The solid lines indicate the temperature ($T$), number density of nuclei ($n$), and number density of electrons ($n_e$). The dotted lines show the ionization fractions of ionic species of oxygen. Full scale is 1. The part of the flow where the greatest drop in temperature occurs is referred to as the "cooling zone." The zone where recombination and the greatest amount of compression takes place is referred to as the "recombination zone."
Figure 1.1
CHAPTER 2

A DETAILED COMPARISON OF X-RAY AND OPTICAL EMISSION

1. Introduction

Its proximity, large apparent size, and high surface brightness have made the Cygnus Loop (the Veil Nebula, NGC 6960, 6979, 6992/5) a favored object for study of adolescent to middle-aged supernova remnants (SNRs). At a distance of roughly 770 pc (Minkowski 1958) the $3^\circ$ diameter of the Loop corresponds to 40 pc at a scale of $1.15 \times 10^{16}$ cm arcsec$^{-1}$. At this scale it is possible to study the optical structure of the Loop at a resolution approaching the scale of the stratification of the cooling and recombination zones responsible for the optical emission. [The reader is referred in particular to two recent optical studies (Fesen, Blair, and Kirshner 1982; Hester, Parker, and Dufour 1983) for descriptions and differing interpretations of the Loop.] It has also been possible to discern a great deal of the X-ray structure of the Loop, even using instruments with relatively poor spatial resolution (e.g., Rappaport et al. 1974, 1979). Most recently the Cygnus Loop was studied using the X-ray imaging systems aboard the Einstein
Observatory by Ku et al. (1984). These studies have found that a gross correlation exists between the portions of the shell which are bright in X-rays and the large regions of filamentary emission which define the remnant optically.

The general picture of the Cygnus Loop which has evolved over the past 15 years is that of a middle aged (~16000 year old) supernova remnant still in the adiabatic phase of its evolution. The X-ray emission from the remnant is consistent with thermal emission behind a 300-400 km s\(^{-1}\) blast wave propagating into a medium of density 0.1-1 cm\(^{-3}\), while the optical emission is primarily due to radiative shocks with velocities of ~100 km s\(^{-1}\) being driven into clouds of density 2-10 cm\(^{-3}\). While this basic picture (first put forward by McKee and Cowie 1975) seems fairly secure (see Falle and Garlick 1982 for a dissenting view), there are a number of pertinent questions upon which there is no general consensus. These questions deal, for example, with the size of clouds in the ambient medium, the applicability of steady flow shock calculations to optical and UV spectra, the three dimensional structure of filaments, and the reason for the large scale correlation of optical and X-ray emission.

In the present paper we present a comparison with a spatial resolution of 17" (high by X-ray standards) between the optical and X-ray emission from an 18' diameter field on
the SE\(^{(1)}\) edge of the Cygnus Loop, using data previously published by Hester, Parker, and Dufour (1983) (hereafter HPD) and Ku et al. (1984) (hereafter KKPL). In Section II we present the data. In Section III we describe the relationship between the optical and X-ray emission in the field, generalizing to the Loop as a whole when possible. In Section IV several possible explanations for the presence of bright X-ray emission in the vicinity of optical emission are presented and evaluated within the context of the data. These mechanisms involve evaporation, gradual variations and gradients in the density of the preshock intercloud medium, and additional compression of material which has already been heated to X-ray temperatures by the adiabatic blast wave. The additional compression could result from rapid deceleration of the blast wave itself or from reshocking by reflected or bow shocks around dense clouds. Section IV also addresses implications of the observations for models of SNR evolution and the interstellar medium (ISM).

\(^{(1)}\)This region of the Cygnus Loop (NGC 6995) has traditionally been referred to as the "SE" on the basis of its position at the southern end of the optically bright eastern limb. While this field lies almost due east of the center of the Loop as defined by the X-ray emission, we maintain the earlier nomenclature.
II. Data

Optical and X-ray imagery are presented for a field ~18' in diameter located on the SE edge of the Cygnus Loop. The optical data consist of [O III] λ5007 and [S II] λλ6725 rasters generated from image tube plates taken at f/7.5 using the No. 1 .91-m telescope at Kitt Peak National Observatory. The plates were digitized using a PDS microdensitometer at KPNO and further reduced using the Rice University Picture Processing System. The data are a subset of those presented by HPD, where the optical morphology and spectral characteristics of the north central part of the field are discussed in detail. These two emission lines were chosen for comparison with the X-ray data because they represent emission from the hottest and coolest parts of cooling and recombination regions behind radiative shocks.

Two overlapping X-ray images of this field obtained using the high resolution imager (HRI) aboard the Einstein Observatory were graciously provided by William Ku of the Columbia Astrophysics Laboratory. These were among the data discussed by KKPL. The net observation times for the two images were 5806 seconds and 5142 seconds. The two frames were normalized according to their exposure times and a vignetting correction was applied to each assuming a 30% correction at 10' off axis. The two were aligned using the field centers and scales supplied with each frame.
transformed to the same "plate scale" as the optical rasters, then combined to form a mosaic which overlays the optical data directly. The X-ray raster is about 19' on a side and contains the circular optical field.

The alignment of the optical data was based on positions for 70 stars in the field and 25 nearby SAO stars measured from a Palomar Schmidt plate. The relative alignment between the two optical rasters is good to 0"3. Based on the errors in a fit to the star positions measured from the Schmidt plate we find the overall uncertainty in the absolute alignment across the face of the optical rasters (due to uncorrected image tube and telescope distortion) to be < 3". The uncertainty in pointing of the HRI is ~10". The HRI has a nominal resolution of about 4".

It was necessary to smooth the X-ray data by convolution with a 17" FWHM Gaussian before relatively clean surface brightness contours began to emerge from the counting statistics.

Figure 1 shows a linear gray scale map of the composite X-ray image. The faintest regions in the field have a surface brightness of ~ .01 counts arcmin$^{-2}$ s$^{-1}$. The brightest knot has a surface brightness of ~.17 counts arcmin$^{-2}$ s$^{-1}$. North is to the top of the figure and east is to the left. Figure 2 shows the optical data after suppression of the bright star centers. The signal to noise ratio of the data has been improved by rejecting pixels > 2σ
from the mean of the surrounding 3 X 3 pixel window. The images have a resolution of ~3". Figure 3 shows logarithmic contours of the smoothed optical data overlaid onto the X-ray image. In order to facilitate comparisons with the X-ray data the optical images were also smoothed to a FWHM of 17" before generation of contours. The contour levels are separated by a factor of 2 in each case.

The most detailed and complete X-ray map of the Cygnus Loop to date (made by merging together 59 Einstein IPC images) has recently been published by KKPL. In their Figure 1 they present this map overlaid onto a POSS image of the Loop. Frequent reference is made to this map in the remainder of the present article, and the reader is advised to have a copy on hand. A color coded version of their map appears in Henbest and Marten (1983), p201.

III. Optical/X-ray Comparisons

A. Overview of the Cygnus Loop

The general appearance of the Cygnus Loop at X-ray wavelengths has been discussed at length by KKPL. The basic appearance is that of a shell in which limb brightening is apparent around the entire circumference. In a limb brightened shell geometry the scale over which the surface brightness drops off at the edge of the shell gives an
estimate of the thickness of the emitting zone. From the radial profiles and composite IPC map in KKPL we estimate a thickness of order 1 pc for the zone of generally bright X-ray emission behind the adiabatic blast wave. The limb brightening is far from uniform, however. In some directions around the Loop the limb brightening is less than a factor of 2, whereas the contrast between the brightest features on the limb and the faintest regions interior to the Loop is a factor of 50. From the radial profiles and IPC map presented by KKPL it can be seen that much of the limb brightened appearance is attributable to emission associated with optical features on the east and west limbs of the Loop. [Similar associations between the X-ray and optical emission have been reported for other remnants. See for example Mathewson et al. (1983) for optical and IPC images of SNRs in the Magellanic Clouds.] The X-ray enhancements on the E and W limbs extend about 30' further around the perimeter of the Loop than do the regions of optical emission with which they are associated. They also extend further toward the center of the Loop. These appear to be large flat regions ("pancakes") with the brightest X-ray emission and the optical emission in the center and fainter X-ray emission toward the edges.

Along the X-ray bright N - NE limb of the Loop there are no bright optical filaments near the rim, although even here the X-ray emission is not completely without
association with optical features. The NE X-ray limb appears to be part of the extended pancake of emission centered on the optically bright E rim, and the bright X-ray emission along the N of the Loop extends toward the center far enough to encompass the region of optical emission at 20\textsuperscript{h} 49\textsuperscript{m} and 31\degree 45\arcmin. (Unfortunately, the IPC map is incomplete in this region, so the details of the association of the X-ray and optical emission are unknown.) The irregularity of the shell and the large scale correlation between X-ray and optical emission emphasize that fits of the total X-ray luminosity of the Cygnus Loop to a Sedov (1959) model (e.g., Tucker 1971; KKPL) give only a rough idea of the average conditions around the Loop. Some direct evidence exists to suggest in particular that the density behind the blast wave in the X-ray bright regions is higher than average. Woodgate, Kirshner, and Balon (1977) used their [Fe XIV] measurements to infer a preshock density of 1 cm\textsuperscript{-3} for the NE limb. As expected from the X-ray appearance, this is considerably higher than the overall rms value of 0.16 cm\textsuperscript{-3} obtained by Tucker and KKPL.

Deviations from circularity around the edge of the Loop are significant. The most striking departure from circularity is the "break-out" in the south which has been interpreted as a direction of much lower than average preshock density. Apart from the break-out, the Loop could
be described as "faceted", with perhaps six facets of roughly equal size around the perimeter.

At four locations around the Loop (three in the SE quadrant and one in the W) there are well defined indentions into the X-ray shell. There is a local maximum in the X-ray surface brightness immediately interior to each of these indentions (KKPL). All of the indentions have some optical emission associated with them. The two indentions which are brightest in X-rays are also the most conspicuous optically, and are located on the optically bright E and W limbs. (It could perhaps be argued that the entire NE facet of the Loop is also such an "indention", but on a much larger scale.) It is a straightforward conclusion from the observations that, when the internal pressure of the Loop is high enough, encountering more material in a given radial direction will retard radial growth, enhance the X-ray emission, and result in a greater likelihood of associated optical emission. The relationship between these effects depends sensitively on the densities available, the amount of time since encountering the higher density, and the manner in which mass is distributed between the various phases present.

KKPL go to some effort to establish the reality of exceedingly faint X-ray emission (~ 30% of the diffuse background) extending ~ 10' beyond the bright shell. This is especially prominent just outside the portions of the shell which are brightest in X-ray emission. If this
emission is physically associated with a precursor of the blast wave (consisting perhaps of suprathermal particles or accelerated material which has overrun and now precedes the blast wave) it would be very interesting. A likely explanation for this emission, however, appears to be scattering of emission from the bright shell by grains in the encountered cloud or the intervening ISM, as has been suggested for the X-ray halos around the Crab and Cas A by Mauche and Gorenstein (1984).

There are several regions of higher than average X-ray surface brightness associated with optical emission across the face (i.e., not the limb) of the Loop (KKPL). The most notable of these is the region of optical emission in the NW part of the Loop (20°47′, 31°20′), often referred to as the "carrot." Regions of optical emission along the rim of the Loop could well be carrot-like regions turned more edge-on. If this is so then the contrast (presumably due to limb brightening) between the moderate X-ray surface brightness at the carrot and the high surface brightness on the rim (a factor of ~ 4) requires that the region of X-ray emission associated with the optical features be fairly thin.
B. Detailed Comparisons for the SE

1) Expectations

We will preface a detailed comparison of the optical and X-ray data with a consideration of the relationships one might reasonably expect. Initially, it seems clear that a general one to one relationship between X-ray features and optical features is not to be expected. The optical emission is thought to arise from very thin ($< 10^{16}$ cm) cooling and recombination regions ($T \approx 10^3 - 10^5$ K) located behind relatively slow shocks (70-120 km sec$^{-1}$) propagating into a medium with a density of order 2-10 cm$^{-3}$, while the X-ray emission is characteristic of thermal emission from a $2 \times 10^6$ K plasma behind an approximately 400 km sec$^{-1}$ adiabatic blast wave moving into a medium with density of order $1-10$ cm$^{-3}$. On the other hand, the rough correlation which exists between the X-ray and optical emission on large scales suggests that conditions which lead to optical

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(2) A detailed 1:1 correlation between optical and X-ray emission may in fact be expected if the scale of the optically emitting clouds is much smaller than the resolution of the images. In this case the warm clouds and the surrounding hot medium would appear to occupy the same volume. This possibility is discussed in Section IV.
emission also favor enhanced X-ray emission from the nearby hot medium. On small scales one might hope to find some pattern in the association between optical and X-ray features which would help to clarify the physical relationships and mechanisms involved.

ii) An Escarpment and XA

Figure 4 shows a schematic drawing of the field in the SE with a number of features and regions labeled for discussion. A steep escarpment in the X-ray surface brightness runs along the eastern side of the field. Immediately to the left of this line the X-ray surface brightness is \( \sim 0.01 \text{ counts arcmin}^{-2} \text{ s}^{-1} \). This surface brightness is comparable to the "unenhanced" limb brightness around much of the Loop, and we refer to this level as the "local shell level." The surface brightness declines to the east of this point down to \( 0.001 \text{ counts arcmin}^{-2} \text{ s}^{-1} \) (which defines the edge of the X-ray shell in the composite IPC map from KKPL) about 10' from the escarpment. The contrast across the escarpment varies from a factor of \( \sim 2 \) to a factor of 17. The lowest surface brightness in the field to the west of this line is \( 0.024 \text{ counts arcmin}^{-2} \text{ s}^{-1} \), which is still a factor of 2 brighter than the emission interior to the Loop about 30' to the west.
The X-ray region XA, located in the SE part of the field, sits at the nose of one of the previously mentioned indentions in the X-ray shell. Figure 5 shows an enlargement of XA. Figure 5a is a linear gray scale map of the smoothed X-ray emission overlaid with X-ray contours. The contours are logarithmic, with each contour separated from its neighbors by a factor of $2^{1/2}$. The lowest contour level is $.035$ counts arcmin$^{-2}$ s$^{-1}$. Figure 5b shows these same contours overlaid onto a logarithmic gray scale map of the unsmoothed [O III] emission. A logarithmic gray scale was used so that both the faint and bright optical structure would be visible. The eastern edge of XA overlaps the field which Teske and Kirshner (1984) imaged in [Fe X] $\lambda6374$ coronal line emission. They found that the coronal line emission has a distribution similar to that of the X-ray emission, but with features loosely correlated with the bright optical nebulosity. The average X-ray surface brightness in the region is $\sim.09$ counts arcmin$^{-2}$ s$^{-1}$. Along the eastern edge of XA the average surface brightness is $\sim.11$ counts arcmin$^{-2}$ s$^{-1}$, 11 times the local shell level. At the SE corner of XA there is a small knot with a surface brightness of $.17$ counts s$^{-1}$ arcmin$^{-2}$, placing it among the brightest X-ray features in the Loop. The knot sits between the branches of a Y formed by two [O III] filaments. Assuming a temperature of $2 \times 10^6$ K, a spherical geometry, and a radius of 10", KKPL calculate a density of 31 cm$^{-3}$ for
this position, and suggest that the density may actually be higher if $T$ is lower. This density is 10 to 100 times the average density behind the adiabatic blast wave (as calculated from Sedov fits to the X-ray data or pressure balance with the optical shocks) and is comparable to the density behind the radiative shocks before cooling.

a) The Optical Appearance of XA

Optically, the vicinity of XA contains a complex of features which are primarily type I.5 and type II. (Type I.5 and type II are HPD's notation for features which are strong in [O III] but weak or absent in emission from optical lines of cooler species.) The X-ray emission in Fig. 5 is roughly divided into northern and southern sections by a somewhat fainter wedge which intrudes from the west. These sections are more or less outlined by the fourth contour level ($\sim .1$ counts arcmin$^{-2}$ s$^{-1}$). The northern section overlays a triangular region of optical emission which includes a closely spaced pair of bright knots, lying about 2' west of the optical edge. These knots are present in both [O III] and [S II]. There is a moderately bright X-ray knot located just to the west of the optical knots. The western part of the southern section of XA, on the other hand, fills a void in the optical emission. The western edge of XA, as defined by the third contour
level in Fig. 5 (.07 counts arcmin$^{-2}$ s$^{-1}$) lies 30" - 45" to the west of a faint N-S [O III] filament.

Within XA there is neither a consistent correlation nor anticorrelation between the optical and X-ray emission. (There are, in fact, striking examples of each.) The eastern and southern borders of XA are another matter. A very striking correlation exists along the eastern edge of XA, where the edge of the bright X-ray emission and the envelope formed by the leading-most optical filaments are coincident to well within the limits of resolution and alignment of the data. The X-ray escarpment follows the optical edge for a distance of well over a parsec. This sharp edge is also present in [Fe X] λ6374 emission (Teske and Kirshner, 1984) and in 49-cm synchrotron emission (Dickel and Willis 1980). At the southern end of XA the X-ray contours above about .05 counts arcmin$^{-2}$ s$^{-1}$ make a sharp turn to the west and follow a group of E-W optical filaments for about 4′ (= .88 pc) before turning again to the south. The N-S ridge in the X-ray surface brightness is still pronounced at the southern edge of the field. From the IPC map it appears that this ridge follows the edge of the optical emission ~ 5′ to the SW.
b) The Geometry of XA

The relationship between the optical and X-ray emission at XA is most easily understood as a thin but distorted sheet of optical emission interior to which is found a somewhat thicker slab of bright X-ray emission. The projected thickness of the bright eastern portion of XA (~1' ≈ .2 pc) provides an upper limit on the physical thickness of the region of enhanced X-ray emission there. (The size of the bright knot, ~ 20", gives an estimate of ~ .07 pc for the thickness of the region.) This is considerably less than that expected for emission behind the adiabatic blast wave propagating into a uniform preshock medium in a typical Cygnus Loop model.

The geometry of the bright knot in XA may not be spherical. When describing bright optical features it is often necessary to invoke a line-of-sight depth much greater than the apparent thickness of the feature (Parker 1967; Miller 1974) or the expected thickness of the radiative zone behind a shock (HPD). (Most filaments are about 15 times as bright as a face-on shock, and factors of up to 50-60 occur -- face on 100 km sec⁻¹ shocks are essentially invisible on our plates.) If the greatest line-of-sight depth in the area is comparable to the N-S elongation of XA (4' ≈ .9 pc -- this trick often works fairly well for the optical data)
then the emission measure given by KKPL (~77 cm\(^{-6}\) pc) gives 
n = 9 cm\(^{-3}\).

c) Pressure Equilibrium?

The knot in XA (and probably all of XA) appears to have 
a considerably higher pressure than generally inferred for 
the post-shock region. Assuming a constant \(N_H = 4 \times 10^{20}\) 
cm\(^{-2}\), KKPL found that the limb temperature is fairly 
constant (within a factor of ~ 2) at about 2.1 \(\times 10^6\) K, with 
a slight anticorrelation between temperature and surface 
brightness. This anticorrelation is in the right direction 
for pressure equilibrium. (A similar but more quantitative 
result has been reported for the Vela SNR by Kahn et al. 
1984.) Thus, the knot may have a slightly lower than 
average temperature, but the inferred densities are high. At 
\(T = 6 \times 10^5\) K (considerably lower than any temperature 
reported by KKPL and probably somewhat too low for strong X-
ray production at all), \(n = 31\) cm\(^{-3}\) and 9 cm\(^{-3}\) give \(p/k = 38\) 
\(\times 10^6\) cm\(^{-3}\) K and 11 \(\times 10^6\) cm\(^{-3}\) K, respectively. This 
compares with \(p/k = 2nT = 2.6 \times 10^6\) cm\(^{-3}\) K for the average 
Sedov parameters and a usual [S II] optical pressure of \(p/k\) 
\(< 7 \times 10^6\) cm\(^{-3}\) K (assuming \(n_e < 10^3\) cm\(^{-3}\), 50% ionization, 
and \(T = 5000\) K).

The relative overpressure of the knot can be 
demonstrated more clearly by comparing its surface
brightness with unenhanced parts of the shell. The line-of-sight depth through the brightest part of a 1 pc thick shell with radius 20 pc is ~ 12 pc. The depth through the brightest part of a shell with radius 20 pc and a limb to center ratio of 3:1 is ~ 24 pc. Thus, for a region only 1 pc deep to appear 17 times brighter than the local shell level requires that it be 15-20 times denser. Since the temperature can’t be more than about a factor of 2-3 lower in the bright regions, this requires that the pressure be higher by a factor of at least 5 - 7.

iii) XB and XC

Just north of XA the X-ray surface brightness drops off to ~0.06 counts arcmin\(^{-2}\) s\(^{-1}\). The optical emission remains strong at this location, especially in [O III]. At this point both the optical and X-ray edges turn to the east with a relatively modest rise in X-ray emission occurring about 30" behind an [O III] arc. The X-ray feature XB (which has a peak surface brightness of ~0.10 counts arcmin\(^{-2}\) s\(^{-1}\)) and the X-ray arc extending NE from there lie just behind the geometrical extension of the [O III] arc. This arc forms the sharp southeastern boundary of the diffuse optical emission to the east of HPD's Region I. This diffuse emission is spectrally similar to the arc itself (see the extreme SE corner of Figures 4 and 5 in HPD) and also fades
out gradually along its eastern edge. Roughly speaking, the appearance is that of a bubble-shaped surface which grows progressively fainter in optical emission toward its eastern end, with XB lying just inside the bubble. There is also a very faint Hα filament [apparently similar to the "pure" Balmer filaments discussed by Raymond et al. (1983) and others] lying near the edge of the X-ray emission between XA and XB.

The bright X-ray region XC has an average surface brightness approximately 8 times the shell level (~0.08 counts arcmin⁻² s⁻¹) and is roughly defined by the ~0.65 counts arcmin⁻² s⁻¹ contour. It is associated with a region of mottled optical emission (HPD’s Region I and its continuation to the north). The SE edge of XC closely follows the edge of the bright [O III] emission in HPD’s Region I. There are a number of locations across XC where small X-ray features lie on top of or just to the west of optical features. The anvil shape of XC generally matches the extent of the [S II] emission, although the X-ray emission extends slightly further to the west than does the optical emission. XC could be explained by a flat ~0.2 pc thick zone of enhanced X-ray emission (much like XA) turned somewhat face on. As is the case with XA the X-ray emission appears to lie physically interior to the optical emission with which it is associated.
There is an irregular region which is very slightly enhanced in X-rays extending to the west of HPD's Region III. This region has an average surface brightness of \(~0.052\) counts arcmin\(^{-2}\) s\(^{-1}\) as compared with \(0.038\) counts arcmin\(^{-2}\) s\(^{-1}\) for the fainter emission between it and XA and \(0.024\) counts arcmin\(^{-2}\) s\(^{-1}\) for the faint region in the NW corner of the field.

There are several regions of strong optical emission which do not show exceptionally bright X-ray emission. The western end of the horizontal bar located just east of Region III shows no enhancement at all in X-rays relative to the surrounding emission, although it is particularly bright in [S II]. HPD's Region IV, located in the northwestern part of the field and visible only in lines from low excitation species, is not strongly enhanced in X-rays. There is also some faint optical emission in the SW corner of the field which is not enhanced in X-rays. Note, however, that even the "unenhanced" X-ray emission in the western part of the field is still fairly bright by the standards of the Loop as a whole.

C. Coincidence of Bright Emission with the Blast Wave

We discussed the striking correlation between an X-ray escarpment and the edge of the optical emission along the border of XA and extending on to the patch of emission 5' SW
of our field. The coincidence between edges of regions of
X-ray and optical emission is also found elsewhere in the
Cygnus Loop. The bright X-ray knot on the W limb discussed
by KKPL appears to be associated with radiative shocks in
much the same way as XA. There is also a close correlation
between the edge of the X-ray shell and the optical features
along the eastern limb of the break-out in the south. KKPL
discuss the correlation of the edge of weak portions of the
X-ray shell with optical filaments which are primarily
visible in Balmer line emission from hydrogen (Raymond et
basis of spectral characteristics and a two component Hα
velocity profile similar to that reported by Treffers
(1981), Raymond et al. (1983) have suggested that the Hα
emission is due to collisional excitation of neutral
hydrogen behind a collisionless non-radiative shock with \( v =
170 \text{ km s}^{-1} \) moving into a medium with \( n_0 \approx 2 \text{ cm}^{-3} \).

An edge in the X-ray emission as sharp as the eastern
border of XA is most easily interpreted as a portion of the
blast wave which is tangential to the line of sight. The
coincidence of optical features with well defined X-ray
escarpments or the edge of the X-ray shell suggests that at
these locations the locus of optical emission is coincident
(within a cooling length of \( \sim 10^{16} \text{ cm} \)) with the current
position of the blast wave. This view is strengthened by
the young age of the optical emission at XA (see Section
The geometry of XA and its location at the nose of an indentation are consistent with an encounter between the blast wave and a cloud having dimensions of a parsec or greater. This may apply to all of the regions of optical emission, with our being prevented from seeing it by the fact that the other regions do not lie as close to the projected edge of the Loop. Cox (1972c) suggested (albeit from somewhat different considerations) that about 12% of the surface of the Loop is covered with radiative shocks. If this estimate is accurate then it is fortuitous that we see optical emission at the actual projected edge at all.

The view that the blast wave and optical emission are coincident is quite different from that of other authors (e.g., Fesen, Blair, and Kirshner 1982; Teske and Kirshner 1984) who assume that complexes of optical emission seen in projection 5' interior to the X-ray edge physically trail the blast wave by a parsec. The difference between these views is perhaps the central issue in understanding the Cygnus Loop.

The strong X-ray escarpment in our field is well correlated with the leading most bright optical filaments. (As discussed above, the same appears to be the case at other locations around the Loop.) Fainter X-ray emission does extend 5 - 10' farther out, however. This tendency for X-ray emission to extend beyond the bright optical filaments (as well as bright X-ray features) is expected from
geometrical effects alone. Since the shell is complete in X-rays, X-ray emission is guaranteed to be seen at the projected edge of the shell. Conversely, the patchy and comparatively rare optical emission should normally be seen near but not at the projected edge. Assuming a perfectly spherical geometry, about 1/3 of the surface area of the Loop is seen in projection within 5' of the edge. At the canonical distance of the Cygnus Loop, a 5' projected distance from the edge corresponds to a spatial distance of 7 pc measured along the shell surface. The observed separation between X-ray and optical edges at best represents only a strong upper limit on the difference in radii between the optical and X-ray shells. The coincidence of the X-ray escarpment with bright optical filaments in our field (and possibly elsewhere) implies that bright X-ray features do occur in conjunction with optical features and that both are patchy, strongly suggesting that both lie at the local outer boundary of the shell.

It might be argued that since line-of-sight tangency is absolutely required to achieve the surface brightness of the optical filaments that they must lie at the projected edge. Such is not the case, however. Even small ripples on a smooth sheet will produce line-of-sight tangencies so long as the average sheet normal is close to perpendicular to the line of sight (Hester 1985b). (The maximum angular difference for achieving tangency equals the angular
perturbations of the ripples.) This effect further enhances the likelihood that the brightest optical features will, in the absence of large scale deformation of the shell, be generally near the projected edge.

Finally, it must be recalled that our field, and XA in particular, lies at the nose of an indentation into the X-ray shell, even as defined by the weak contours. Similar indentions are accompanied by bright X-ray and optical emission at other locations as well. Emission located at the nose of an indention will always appear in projection to line interior to the apparent edge, even if it is physically coincident with the local outer boundary of the shell.

In summary, there is no compelling evidence that the regions of bright optical emission are all substantially interior to the local outer boundary of the shell (i.e., the local position of the blast wave), and in fact it seems almost certain that many are not.

D. Recency

In the notation of HPD, the optical emission associated with the bright X-ray region XA, and in particular the emission coincident with the edge of XA, is type I.5 to type II. HPD follow others (Raymond et al. 1980a; Fesen, Blair, and Kirshner 1982) in interpreting type II emission as due to emission from young incomplete cooling regions. This
implies a recent encounter between the blast wave and the cloud since the degree of completeness of the cooling region is directly related to the amount of time since the material behind the shock first began to radiate. This interpretation is strengthened by the fact that feature type correlates with the spatial order of features in the way expected (HPD) with the incomplete cooling regions generally found ahead of complete cooling regions. The transition from a non-radiative shock to a radiative shock approaching steady flow can be seen along the length of the [O III] arc between XA and XB. At its western end, this arc is visible in relatively cool lines like Hα and [S II], as well as [O III]. Moving to the east and north, the arc disappears in all lines but [O III], then fades out in the optical entirely, only to appear again in X-rays about 30" further along. (We predict that UV observations of the gap would show the presence of a shock with $v > 130\ \text{km sec}^{-1}$.)

This appears to be the location where the blast wave is attached to the cloud or portion of a cloud responsible for the optical emission at XA.

In contrast to XA, HPD's Region III [the vicinity of Miller's (1974) position 2] seems a very good candidate for a cloud which has in fact been largely or wholly engulfed by the blast wave. It is the site of very bright optical emission from lines ranging in ionization state from $O^{++}$ through $S^+$ and $O^0$, which implies that the blast wave hit the
cloud (or passed through the region) much longer than a cooling time ago. The geometry of Region III and the filaments which emanate from it to the NE and SE further suggest that it is a significant indentation into the shell. The projected distance of Region III behind the edge of the bright optical emission is slightly over a parsec. Despite its evolved state, this region is not at all conspicuous in the X-ray image. It appears then, at least for the field studied, that exceptionally bright X-ray emission must be viewed as a phenomenon associated with a recent encounter with the blast wave, rather than a phenomenon associated with prolonged exposure to the hot medium behind the blast wave.

E. Synopsis

A physical description of the Cygnus Loop must accommodate the following facts:

At X-ray wavelengths, the Cygnus Loop is a limb-brightened shell with a thickness of \( \lambda \) 1 pc and a limb to center ratio of roughly 3:1 to 5:1. There are extended pancakes of X-ray emission (which are about a factor of 2 brighter than the unenhanced shell) surrounding regions of exceptionally bright X-ray and optical emission. The brightest X-ray emission lies at noses of indentions into the shell. Optical features are at several locations
coincident (at least down to scales that can be judged from the IPC map) with edges or ridges in the X-ray emission.

On smaller scales there are regions of X-ray emission (e.g., XA and XC) which are ~10 times brighter than the unenhanced shell. These regions sometimes agree in general extent with regions of optical emission, although regions of optical or X-ray emission exist without counterparts in the other band. In particular, an evolved region of optical emission located ~1 pc west of the projected bright optical edge is not particularly bright in X-rays. When optical and X-ray emission do go together, the X-ray emission appears to physically lie just interior to the optical emission. (We find no compelling evidence to support the claim that optical filaments lie substantially interior to the local position of the blast wave.) Within the bright X-ray regions are smaller features which are a factor of ~2 brighter still. The regions of brightest X-ray emission seem to be significantly out of pressure equilibrium with the rest of the shell’s interior.

At the scale of our resolution there is no general 1:1 correlation between X-ray and optical emission. A significant exception to this occurs along a sharp escarpment in the X-ray surface brightness across which the surface brightness jumps by a factor of 2 to 17. The escarpment is coincident with young ($\leq 10^3$ year old) optical emission over a length of $>1$ pc.
IV. DISCUSSION

The gross correlation between optical and X-ray emission has lead some authors to suggest that the clouds responsible for the optical emission may be evaporating and that the evaporated material is enhancing the X-ray emissivity (e.g., Cowie, McKee, and Ostriker 1981; KKPL) and coronal line emissivity (e.g., Ballet, Arnaud, and Rothenflug 1984; Teske and Kirshner 1984) of the intercloud medium. We will discuss evaporation and attempt to evaluate its effect on X-ray emission quantitatively. We will also consider three alternative means of achieving brighter than average X-ray emission based on conditions which will almost certainly be present and which may be more important than evaporation. These are: (1) a pre-existing higher density of the preshock intercloud medium in the vicinity of the clouds responsible for the optical emission; (2) an increase in the pressure behind the blast wave caused by rapid deceleration as it runs up a density gradient; and (3) further compression and heating of the hot post-blast flow by reflected or bow shocks associated with dense clouds.

A. Two Pictures of the Cygnus Loop

Before discussing evaporation we will outline the overall physical picture it presupposes. Briefly, the blast
wave enters a region containing many clouds or cloudlets and propagates more or less unimpeded through the intercloud medium. Radiative shocks are driven into the clouds, giving rise to the optical emission. The clouds are engulfed by the hot flow behind the blast wave and partially or completely evaporate, enhancing the density of the X-ray emitting intercloud component. Since for a range of temperatures the X-ray volume emissivity of the intercloud medium increases faster with density than it decreases with temperature, the evaporated material has the net effect of enhancing and softening the X-ray emission.

Variations of this picture, coupled with the notion of thermally unstable cloud collapse and/or extremely small cloudlets, have been used by a number of authors to explain the filamentary structure of SNRs such as the Loop (e.g., McKee and Cowie 1975; Dickel and Willis 1980; Smith and Dickel 1983), the correlation of optical and radio emission (Straka et al. 1983), optical and UV spectra which suggest the existence of nonsteady flow shocks (Raymond et al. 1980a; Fesen, Blair, and Kirshner 1982), and the variations in the appearance of the Loop when viewed in the light of different emission lines (Fesen, Blair, and Kirshner 1982).

We find it somewhat difficult to compare our observations with this picture because it does not really represent a single viewpoint. No proponent has ever tried to present it in a consistent form, taking into
consideration all of the relevant observations. The question of cloud sizes is central to this difficulty. The standard model of an evaporative SNR is that of Cowie, McKee, and Ostriker (1981) who use cloud radii of order 2 pc and integration step sizes which smooth over the structure on the scale of our observations. Fesen, Blair, and Kirshner (1982) use cloud sizes which are $\ll .01$ pc and view the optical filaments essentially as ensembles of these tiny cloudlets. KKPL and Teske and Kirshner (1984) discuss clouds with sizes between .06 and .12 pc in order to account for fluctuations in the X-ray and [Fe X] surface brightness. An additional difficulty is that the dynamical effects of the clouds on the propagation of the blast wave itself have not been adequately discussed. If the cloud filling factor is large (which it must be if evaporation is to affect the intercloud medium as dramatically as the data seem to suggest and if the optical surface brightness is to be achieved), then the assumption that the blast wave propagates freely through the intercloud medium may not be valid. Even without considering the evaporated material, the drag and/or "shadows" of clouds could significantly affect the flow behind the blast wave. (The situation may be analogous to forcing a fluid through a porous plug.) A model of the propagation of the blast wave through a cloudy medium which (1) kept track of the dynamical effects of clouds and the material evaporated from them and (2)
followed the fate of the optical, X-ray, and coronal line emission would be very useful. It is our feeling that such a model would have difficulty in simultaneously accounting for all of the phenomena that this picture has been invoked to explain.

A different physical picture has also been used to explain the filamentary and spectral structure of the Loop (HPD; Hester 1985b). If the clouds responsible for the optical emission are as large as filament lengths or larger [perhaps resembling "standard" interstellar clouds (Spitzer 1978), or even outer portions of molecular clouds], and if thermal instabilities are relatively ineffective in fragmenting the cooling region (as is suggested by the ubiquitous presence of small scale features emitting in a wide range of emission lines) then the source of the optical emission would more closely resemble a thin (~ 10^{16} cm) sheet working its way into the cloud. In this view the projected linear extents of the regions of optical emission around the Loop may be characteristic of the cloud sizes. In other words, the entire E, NE, and W optical limbs could each represent a single large cloud. (It is well known, but often overlooked, that just such a cloud is probably needed to explain the contrast in star counts on the blue POSS print across a line which coincides with the edge of the optically bright W limb.) DeNoyer (1975) found that there are HI clouds adjacent to the optical nebulosity in the W
and NE. Assuming a line-of-sight depth of 5 - 10 pc she calculated densities of 5 - 10 cm$^{-3}$. The agreement of the average HI density with the cloud density inferred from the optical data requires a cloud filling factor close to unity, and can be most easily explained by single clouds 5 - 10 pc in extent. The distribution of such clouds around the perimeter of the Loop could perhaps have been influenced by the supernova precursor (e.g., McCray and Snow 1979; Shull et al. 1984).

Hester (1985b) demonstrates that variations in projected line-of-sight depth along the sort of deformed thin sheet required in this second picture result in a filamentary morphology remarkably similar to that of the Cygnus Loop. [Such a geometry for the filaments was first proposed by Poveda and Woltjer (1968).] This picture accounts for the observation (HPD) that the optical filaments in the Loop are generally not spectrally discrete from the diffuse emission in which they lie and the fact that the depth of the filaments must be many times their apparent width. Filaments are also often seen to bound regions of diffuse optical emission (e.g., the [O III] arc between XA and XC and the fork-like filaments north of center), which strongly suggests limb brightening in a thin sheet. In this picture, variations in the appearance of the Loop when viewed in different emission lines arise from systematic variations in the physical conditions (e.g.,
shock velocity and completeness of the cooling region) along the face of the sheet. The coronal line emission would arise predominately in shocked intermediate density material.

The observed correlation of radio and optical features is explained in the standard way using field compression along with "betatron" acceleration of cosmic rays (van der Laan 1962a,b). Straka et al. (1983) noted an apparent truncation of the radio behind [S II] and suggested that it could be explained by a rarefaction wave (Straka 1984). Other possibilities for such a truncation include the limited lifetime of accelerated cosmic ray particles against escape from the regions of compressed fields, lower compression and acceleration in the slower shocks responsible for the low excitation filaments, or a sufficiently recent encounter that there simply isn't any dense material behind the [S II] zone. Any of these explanations could probably be applied to either view of the cloud scale.

B. Small Cloudlets?

The preceding section makes it clear that a crucial parameter in explaining not only our data but all of the data on the limb of the Cygnus Loop is the characteristic size of a cloud in the preshock medium. Judging from the
optical and X-ray appearance of the Cygnus Loop, inhomogeneities obviously exist in the surrounding ISM on scales ranging from \(< .1 \text{ pc} \) to \(> 10 \text{ pc} \). It is not clear, however, when to call such inhomogeneities "clouds." For the purposes of the current discussion a "cloud" can be thought of as a contiguous region in which the ambient density is high enough for the formation of a radiative shock at the applicable pressure. While this definition is very pragmatic and far from universal, it is obviously useful when discussing the optical morphology. It is also appropriate when discussing the X-ray emission because it takes a "non-radiative" shock to heat the "intercloud" medium to temperatures which can emit X-rays and/or drive significant evaporation. Finally, this definition is appropriate from a dynamical standpoint because it is the material behind radiative shocks which cools and is compressed, leading to very dense regions behind the blast wave.

HPD argue that the optical morphology and spectral structure of the Cygnus Loop require clouds which are large enough for the formation of steady flow shocks and certainly no smaller than the lengths of filaments. Hester (1985b) further shows that complexes of short filaments can arise from a single shock front moving into a large cloud. An alternative view of the Cygnus Loop holds that the clouds are exceedingly small \((\ll .01 \text{ pc})\) and that optical features
are really ensembles of these unresolved cloudlets. This picture was proposed by Cowie and McKee (1975) and used by Fesen, Blair, and Kirshner (1982) to account for features showing nonsteady flow spectra. Clouds which are smaller than a filament length but larger than .01 pc are excluded by the optical data. They would be easily resolved, and are just not seen.

The evidence favoring large clouds is outlined above. An attempt to explain the optical morphology with the small (<< .01 pc) cloudlet picture leads to a number of implausible statements about the ISM. (1) Small cloudlets were invoked to explain filaments which were not seen in all emission lines and the separations between such filaments. To explain the presence of features which are seen in a range of lines, however, requires that cloudlets of a wide range of densities be present. This is necessary so that different cloudlets will have cooled to the point of emitting different lines in the same amount of time. [This also rules out large but very thin sheet-like clouds such as those proposed by McKee and Cowie (1975). It does not rule out sheet-like clouds which are thick enough for the formation of complete cooling and recombination regions behind radiative shocks.] (2) A spatially homogeneous distribution of cloudlets would result in emission which is smeared out behind the blast wave, rather than the filamentary structure observed. Thus filaments must reflect
the structure of pre-existing agglomerations of cloudlets in the ISM in front of the blast wave. (3) The sharpness of filaments requires that the pre-existing agglomerations have very abrupt edges. (4) If the filaments have been engulfed by the blast wave, the pre-existing agglomerations must be very thin. (5) The optical brightness of filaments requires exceedingly large cloudlet filling factors within the pre-existing agglomerations of cloudlets. (6) The agglomerations must be sheet-like rather than filamentary to account for the large line-of-sight depth through the emitting region. (7) In the small cloudlet picture, optical spectra will primarily reflect the underlying spectrum of cloudlet densities. For filaments to be spectrally indistinguishable from the surrounding diffuse emission (HPD) the spectrum of cloudlet densities must be the same in and between agglomerations. (8) To account for the agreement in spectral properties of filaments from all around the remnant (HPD), the spectrum of cloudlet densities must be fairly constant everywhere. In short, while the small cloudlet picture was an interesting idea, it leads to consequences for the ISM which are highly implausible.

C. Evaporation of Clouds

The "standard" explanation of the large scale association between X-ray and optical emission in SNRs such
as the Cygnus Loop is evaporative enhancement of the intercloud medium. We will try to evaluate the effect on the X-ray emission both for an isolated cloud or cloudlet and for a general enhancement of the intercloud medium by material evaporated from many small cloudlets.

1) Evaporation of Isolated Clouds

The X-ray emission from the evaporatively enhanced medium around an isolated cloud is an important calculation for two reasons. First, this is the mechanism suggested by KKPL to account for the bright knot at the corner of XA. Teske and Kirshner (1984) also attribute the clumpiness of the [Fe X] data to evaporation from many small cloudlets. Second, this approximates the early phase of the general enhancement of the intercloud medium by evaporation from many cloudlets.

A number of models of thermal X-ray emission from a hot plasma have been constructed (e.g., Tucker and Koren 1971; Kato 1976; Raymond and Smith 1977). These models indicate that at temperatures around $2 \times 10^6$ K line emission dominates the X-ray spectrum. To obtain an X-ray emissivity we summed the line emission from Raymond and Smith (1977) models over an energy range from .1 keV to 4 keV (to approximate the response of the HRI). The model temperatures ranged from $1.6 \times 10^5$ K to $4 \times 10^6$ K. These
emissivities were adjusted slightly to account for contributions from continuum emission using values read from Figure 2 in Raymond and Smith. We then assumed pressure equilibrium between the evaporatively enhanced region and the surrounding material and scaled the emissivities by $T^{-2}$ ($\propto n^2$) to obtain relative volume emissivities as a function of temperature (or density). This function peaks around $6 \times 10^5$ K, where the volume emissivity is up by a factor of about 4 with respect to emission at $2 \times 10^6$ K. Overall, the temperature dependence of the X-ray emissivity in this domain is fairly flat, and it is the variation in $n^2$ which dominates the volume emissivity.

The standard model of evaporation is that of Cowie and McKee (1977) who calculate the steady state evaporation from a spherically symmetric cloud sitting in a hot medium of temperature $T_f$ far from the cloud. If the evaporative flow from a cloud is subsonic and unsaturated then it is approximately isobaric. Cowie and McKee (1977) showed that this holds for values of the global saturation parameter $\sigma_0 \ll 1$. This seems to hold for plausible values of the post-shock intercloud density $n_1$, $T_f$, and cloud radius $R_c$ for the Cygnus Loop (although the heat flow into extremely small cloudlets may be saturated). Draine and Giuliani (1984) found that for $\sigma_0 = 1$ (the smallest value of $\sigma_0$ for which they plotted pressure) that the pressure at the cloud
surface is only ~50% higher than the pressure far from the cloud.

Note that if \( \sigma_0 > 1 \), then the \( \dot{m} \) used below is too large. We have also neglected the greater extinction at lower energies which will make lower temperature emission appear fainter. Thus the present effort may overestimate evaporation and its affect on the observed X-ray emission. Given the association of bright X-ray emission with young optical emission, the most severe approximation we have made is probably that the evaporative flow has reached steady state. Time dependent calculations of evaporation in this early phase would be useful.

We convolved the evaporative temperature profile from Cowie and McKee (assuming \( \phi = 1 \), corresponding to evaporation uninhibited by magnetic fields) with the isobaric volume emissivity described above and integrated outward to obtain the average effect of evaporation on the total X-ray emission internal to a given radius. We began the integration at the cloud center to account for the fact that the cloud is a "hole" in the X-ray emission. Figure 6 shows plots of the total X-ray emission for \( T_{6f} (= T_f/10^6 \text{K}) \) = 1, 2, and 4. The results are normalized to the emission from the same volume in the absence of the cloud or the evaporated material. For \( T_{6f} = 2 \) the volume emissivity peaks within 10% of a cloud radius from the surface of the cloud. The emission from this thin shell is ~3 times greater than
the unenhanced case. For $T_{6f} = 4$ the peak enhancement in
the emission from a thin shell bounded by the cloud surface
(a factor of ~11.5) comes within $1.01 R_c$. The filling factor
for this shell is small however. The net increase in X-ray
emission over the volume interior to $1.5 R_c$ is only a factor
of 1.7 and 2.7 for $T_{6f} = 2$ and $T_{6f} = 4$, respectively. The
calculated enhancements do not seem adequate to account for
the observed total brightness of the knot in XA (a factor of
17 over the "local shell level") or even the fainter region
XB. This is especially true because the line-of-sight depth
through the enhanced region around the cloud is likely much
smaller than the depth through the surrounding unenhanced
medium. (It could conceivably account for the factor of 2
enhancement of XA over the brightness of its immediate
surroundings, however.)

It is tempting to increase the temperature $T_f$ to a
large value, thereby increasing the overall X-ray emission
from the evaporated material, and then say that the observed
temperature of $2 \times 10^6$ K comes from this denser, cooler
medium. To evaluate this possibility we calculated an
average value for the temperature of the evaporative flow
defined by

$$<T> \equiv \frac{\int_{R_c}^R T^* L(T) n^2(T, T_f) dV}{\int_{R_c}^R L(T) n^2(T, T_f) dV}.$$
Table 1 gives the results of this calculation for various parameters. Generally we find \( <T> \geq (2/3)T_f \). The observed temperature \( 2 \times 10^6 \text{ K} \) is not consistent with a \( T_f \) much higher than \( 3 - 4 \times 10^6 \text{ K} \). We will also discuss below why the initial intercloud temperature should not be much higher than the temperature after evaporation.

If the evaporating cloud is large then regions such as XA and XB could be the evaporatively enhanced zones close to the surfaces of individual clouds. This picture better fits the observed geometry of XA, and a (time dependent) calculation of the early stages of evaporation from a plane surface would be helpful in evaluating this possibility. It is likely that evaporation will be less efficient in this case. Evaporation off of the face of a large cloud would have to occur across the aligned and compressed magnetic field associated with the radiative cloud shock, and will be further hampered by the opposing flow of surrounding material toward the cloud surface.

11) General Enhancement of the Intercloud Medium

If one persists in believing in an abundance of small cloudlets then the best hope for significant evaporative enhancement of X-ray emission is in using it to enhance the density of the intercloud medium as a whole. This approach was used by Ballet, Arnaud, and Rothenflug (1984) who fit
the [Fe X] and [Fe XIV] coronal line data of Woodgate, Kirshner, and Balon (1977) and Lucke et al. (1980) with an evaporative model. They found that the data required a large cloudlet filling factor (~1/3) and expressed concern that the evaporation may be self-quenching.

a) Effect of Evaporation on the Propagation of the Blast Wave

The blast wave is often considered to propagate freely through the intercloud medium. However, if the evaporated material is to become a significant fraction of the intercloud medium (the observations seem to require that it dominate the intercloud medium) then there must be a pressure gradient across the evaporation region in order to accelerate the newly evaporated material (Cox 1979; Cowie, McKee, and Ostriker 1981). Assuming that evaporated material is accelerated to $(3/4)v_s$ at the time of evaporation, the standard equations of continuity of mass, momentum, and energy can be used to relate the flow at a point "x" in the evaporation region to the flow in front of the blast wave. Let $\langle \rho_0 \rangle$ denote the average preshock density of the material which has wound up in the intercloud medium at point "x". (E.g., $\langle \rho_0 \rangle = \rho_{IC,0}$ if "x" is taken to be just behind the blast wave where no evaporation has taken place, and $\langle \rho_0 \rangle$ equals the average total preshock density for a point "x"
where evaporation is complete.) The solution is

\[
\frac{\rho_e}{\langle \rho_0 \rangle} = 4
\]

and

\[
p_e = \frac{3}{4} \rho_0 v_s^2.
\]

The intercloud pressure just behind the shock itself (where conditions in the intercloud medium behind the shock are denoted by the subscript 1) is

\[
p_1 = \frac{3}{4} \rho_{IC,0} v_s^2
\]

so

\[
\frac{p_1}{p_e} = \frac{\rho_{IC,0}}{\langle \rho_0 \rangle}
\]

and \(T_e = T_1\). In short, for poor dynamical coupling between the clouds and the intercloud component, the temperature in the flow is constant while the density and pressure rise proportionally.

If the evaporated material dominates the intercloud medium well behind the shock, then \(p_1 \ll p_e\). The pressure immediately behind the blast wave, driving it through the unenhanced intercloud medium, will be much lower than the pressure inside the shell. Furthermore, the evaporation zone is approximately isothermal, and the characteristic temperature of the X-ray emission is related to the actual blast wave velocity in the same way as in the homogeneous case (i.e., an observed temperature of \(2.4 \times 10^6\) K implies \(v_s = 400\ \text{km s}^{-1}\)).
b) Scale for Evaporation

The rate at which mass is evaporated off of clouds determines the density and pressure gradients behind the blast wave. The rate of change of the intercloud density is

$$\dot{\rho}_{IC} = \frac{N_C \dot{m}}{(1 - f)}$$

where $N_C$ is the number density of clouds, $\dot{m}$ is the mass loss rate from a single cloud, and $f$ is the cloud filling factor. For the case of unsaturated evaporation, uninhibited by magnetic fields, Cowie and McKee (1977) find

$$\dot{m} = 2.75 \times 10^4 \frac{T_{5/2}^5}{R_c^2} \frac{T}{f} \text{ g s}^{-1}$$

where the Coulomb logarithm has been set to 30. Integrating the equation for $\dot{\rho}_{IC}$, substituting for $N_c = \frac{3}{4}\pi R_c^3 f$, and dividing by the average atomic mass gives

$$n_{IC} = 4n_{IC,0} + 3.30 \times 10^{-6} \frac{f}{1-f} \frac{T_{6f}^{5/2}}{R_c^2} t(\text{yr}) \text{ cm}^{-3}$$

where $t$ is the time since the passage of the blast wave.

The X-ray emission will increase roughly quadratically with time and distance behind the blast wave until the clouds have been completely evaporated. The time during which clouds will evaporate completely is given by Cowie and McKee (1977):

$$t_{\text{evap}} = \frac{m}{\dot{m}} = 3.3 \times 10^5 \frac{n_c R_c^2}{R_c^2} T_{6f}^{-5/2} \text{ yr.}$$
To account for the correlation between the optical and X-ray emission along the eastern edge of XA we will compare the time needed to evaporatively enhance $n_{IC}$ with the time required for clouds to cool enough for the production of optical emission. We will take $n_{IC,0} = .16 \text{ cm}^{-3}$ from the Sedov fits and ask how long it takes to enhance $n_{IC}$ by a factor of 4. (This is about what is needed to explain the contrast across the X-ray escarpment along XA.) We will also take $f = 1/2$, which is close to optimal for evaporation given the roughly $(1-f)f^2$ dependence (for small $f$) of the emission measure of the intercloud material. This may significantly overestimate the X-ray emission. The filling factor of clouds engulfed by the blast wave will decrease as the clouds cool. This robs the intercloud medium of thermal energy, reduces the evaporative mass loss by decreasing $R_c$, and increases the volume to be filled by the hot material. We will neglect these adverse complications.

First we will evaluate the small cloud picture. Taking $n_{IC,0} = .16 \text{ cm}^{-3}$, $T_{6f} = 2$, $n_c = 10 \text{ cm}^{-3}$, and $R_c = .01 \text{ pc}$ gives a time of $\sim 10$ years for a factor of 4 increase in the intercloud density behind the blast wave and a time of $\sim 60$ years for complete evaporation. These times compare with $\sim 700/n_c = 70$ years for the clouds to cool enough to be seen in [O III] and $\sim 2000/n_c = 200$ years for [S II] emission to show up (Raymond et al. 1980a). The rise in the general X-ray emission occurs almost immediately behind the shock wave
(not 1 pc, as supposed by some authors) and the clouds are likely to evaporate completely before cooling sufficiently to emit optical radiation. There is very little observational difference between this case and the case with no clouds and a denser homogeneous preshock medium.

If the cloud radii are taken to be .1 pc [this is about the size suggested by Teske and Kirshner (1984)], then the time scale for a factor of 4 increase in density is 1000 years and the clouds do not evaporate completely for 6000 years. In 1000 years a 400 km s\(^{-1}\) blast wave will travel .4 pc (≈ 2' at d = 770 pc). This is consistent with the view that the bright X-ray emission at XA is well behind the blast wave (marked by the projected lower brightness edge). The rise in the X-ray emission from the projected outermost edge of the shell to XA occurs abruptly at the escarpment rather than quadratically, however. This view also does not explain the close agreement in position between the X-ray and optical edges. The rise of the optical emission should still trail the blast wave by less than 10", putting it close behind the outermost X-ray contour rather than on the X-ray peak.

To account for the close correlation between the X-ray and optical emission at XA we can require cloud parameters such that there is a factor of 4 enhancement of the intercloud density in a cooling time. For \(T_{\text{6f}} = 2\), \(R_{\text{c}} = .024\) pc will give X-ray and [O III] emission together at a
distance of about .03 pc (= 8") behind the blast wave. The time for complete evaporation of cloudlets is $t_{\text{evap}} = 340$ years, corresponding to a distance of 0.13 pc (= 36"). This isn't too different from what is observed, but does not change the fact that .02 pc cloudlets are inconsistent with the optical morphology. We are also uncomfortable with the degree of fine tuning required.

If the correlation of the optical and X-ray emission were due to evaporation from the pre-existing agglomerations of cloudlets required by the small cloudlet picture, then a detailed small scale correlation between the X-ray and optical emission should exist everywhere, and not just at the leading edge of XA. This is not observed.

If the clouds in the preshock medium are much larger than the resolution of the optical and X-ray data then the evaporative time scale will be long compared to the age of the remnant, and evaporation should be an ongoing process throughout. The X-ray brightness should increase toward the center of the Loop, at least for a distance of a parsec of so. This is just the opposite of what is observed when comparing XA and HPD's Region III. Region III is the clearest example of a largely engulfed cloud or cloud complex in our field, yet it does not show up as an X-ray enhancement.
D. A Non-Evaporative Model

In this section we will begin with the "large cloud" view and consider what happens to the X-ray emission as a result of higher preshock densities and dynamical compression of the hot plasma behind the blast wave.

1) Higher Preshock Density

In standard models of the ISM an enhancement of the diffuse medium in the vicinity of the cloud cores could be expected as warm diffuse envelopes form around clouds exposed to the interstellar UV flux and hot coronal gas (e.g., McKee and Ostriker 1977). [Although the time taken for these envelopes to completely form may be longer than the average time between "stripping" by shocks (e.g., Heathcote and Brand 1983), there is still expected to be some envelope present for the shock to strip.] A denser than average intercloud medium in the vicinity of dense clouds provides a straightforward explanation of the large scale correlation between optical and X-ray emission. So long as the temperature behind the blast wave remains high enough, a denser preshock intercloud medium will always increase the X-ray emissivity behind the blast wave more efficiently that trying to evaporate the same amount of material from clouds. This picture leads directly to the
observed "pancakes" with optical cores and extended wings of brighter than average X-ray emission.

Variations in the density of the preshock "intercloud" medium can account for regions of bright X-rays not associated with optical emission, whereas evaporation requires the presence of the dense clouds which are seen at optical wavelengths (unless the clouds evaporate completely before cooling). A denser "intercloud" medium could also explain the association of X-ray emission with indentions in the Loop. The break-out in the SW may be an example of the complementary situation where a lower than average density has resulted in faint X-ray emission and a protrusion of the shell.

There is independent evidence in favor of a pre-existing intermediate density medium. Such a medium has been proposed by Raymond et al. (1980b, 1983) to account for Balmer line filaments coincident with the edge of the X-ray shell (although the shock velocity they obtained may not be high enough for X-ray emission). A low resolution (~2') broad band ultraviolet (1300Å - 1800Å) image of the Cygnus Loop obtained with the FAUST instrument aboard Spacelab 1 (Bixler et al. 1984) shows faint emission from the region of the NE X-ray limb (J. Bixler, 1984, private communication). We suspect that this will also be found to require a post-blast temperature there somewhat lower than $2 \times 10^6$ K and a higher than average density.
ii) Rapid Deceleration of the Blast Wave

As a spherically symmetric blast wave expands into a homogeneous medium it sweeps up additional material and decelerates. The deceleration produces an effective "gravity" in the frame of the shock which gives rise to the drop in pressure behind the blast wave toward the center of the remnant, as in the standard Sedov solution. If there is a steep positive gradient in the density of the preshock medium the blast wave decelerates more quickly, the effective "gravity" in the frame of the shock increases, and the magnitude of the rise in pressure toward the edge of the shell grows as its "scale height" decreases. An example of this can be found in Cox and Franco (1981) who consider Sedov's (1959) self-similar blast wave solutions for power law density distributions. In the case where \( n_0 = R^4 \), for example, the pressure rise occurs over the outer 1/10th of the radius of the remnant, rather than over the outer 1/3rd of the remnant as it does in the case of a flat density distribution.

The degree to which a density gradient will affect the pressure can be estimated by calculating the pressure required to decelerate the material in the shell. Assuming that the preshock density has been constant throughout the expansion of the remnant, the mass per unit area in the shell will be about \( (1/3)R \rho_0 \). The material in the shell
must decelerate at $3/4$ the rate of deceleration of the blast wave, which requires a pressure differential

$$\delta p = \frac{1}{4} R p_0 v_{b0}'.$$

This *"deceleration pressure"* as a fraction of the pressure behind a blast wave moving into a medium of density $p_0$ with a velocity $v_{b0}$ is

$$\frac{\delta p}{p(v_{b0})} = \frac{1}{3} R \frac{v_b}{v_{b0}} = \frac{1}{2} \frac{v_b}{v_{b0}} (\text{Sedov, homogeneous}).$$

This simple treatment can overestimate $\delta p$ because it is not necessary to slow the entire shell at once. The increase in pressure throughout the thickness of the shell will occur roughly in the sound crossing time for the thickness of the shell ($\sim 0.15R/v_b \approx 7500$ years for the typical Cygnus Loop model). A decrease from 400 km s$^{-1}$ (the "average" blast wave velocity) to 200 km s$^{-1}$ (about the minimum velocity necessary for X-ray production) in a crossing time gives $\delta p/p(v_{b0}) = 1$. The lower temperature and higher pressure require a larger $n$ and hence brighter X-ray emission.

These numbers are highly uncertain, although the conclusion that the pressure enhancement at the edge derived from the momentum of the shell can be comparable to the the original pressure is probably secure. The magnitude of the result is consistent with the effect of momentum
conservation in the Sedov solution. Detailed models are needed to better evaluate the effects of gradients in preshock conditions on the X-ray emission and overall dynamics.

Rapid deceleration of the shell will affect X-ray emission in two ways. First, there will be inertial compression of the hot previously shocked material behind the blast wave as it slows down and part of its momentum is converted to pressure. Second, the increase in pressure will further enhance the effects of a higher preshock density discussed above by driving a shock with a greater than expected velocity into the denser medium. The result is that a higher density in the X-ray emitting zone is achieved \( (4n_0) \) with less of a temperature drop than expected from pressure equilibrium. A substantial increase in X-ray emission is thus possible.

It should be noted that the conditions leading to bright X-ray emission are only slightly less extreme than those leading to an even higher density, lower temperatures, and radiative shocks. Thus a close association is expected between bright X-ray emission and optical complexes just from the sensitivity of the emission behind the blast wave to small changes in the preshock density. Near the intersection of the blast wave and a cloud, the X-ray emissivity will increase with density until it dies very abruptly, just before the onset of optical emission. This
might account for the location of XB just beyond the time of an [O III] arc.

iii) Reflected and Bow Shocks

The encounter of a blast wave with a cloud has been discussed by a number of authors (e.g., McKee and Cowie 1975; Spitzer 1982; Heathcote and Brand 1983). The basic assumptions in most treatments of such encounters are that the clouds are spherical, the edges of the clouds are abrupt, and the clouds are sufficiently dense to be considered incompressible for the purposes of calculation of the reflected shock. (Reflected shocks could also form around "bumps" on the surface of a larger cloud.) Figure 7 shows the geometry of the encounter. The notation used is standard, with 0, 1, 2, and c denoting conditions ahead of the blast, behind the blast, behind the reflected shock, and in the cloud, respectively.

The very early stages of the encounter between the shock and the cloud are essentially the same as a normal encounter with a rigid plane. Assuming $\gamma = 5/3$, Courant and Friedrichs (1948) find for this case that $P_2/P_1 = 6$. Depending on the Mach number of the flow behind the blast wave with respect to the cloud (and hence on the Mach number of the blast wave), the reflected shock either dissipates as an acoustic wave or becomes a standing bow shock (which also
dissipates eventually). Since the transition between the two cases occurs at $M_s$ (the Mach number of the blast wave) = 2.76 (e.g., Spitzer 1982) it is likely that most of the reflected shocks do not quickly dissipate. The pressure $p_3$ at the stagnation point at the nose of the cloud will be somewhat lower than the pressure immediately behind the bow shock. The stagnation pressure has been calculated by McKee and Cowie (1975). Table 2 (adapted from Spitzer, 1982) lists properties in the regions of interest as a function of the Mach number of the blast wave.

In the case of blast wave propagation through a cloudy medium the X-ray emission should be exceptionally strong behind the reflected and bow shocks where material that has already been heated to X-ray temperatures by the blast wave is subjected to additional heating and compression. Since the blast wave of the Cygnus Loop is in the strong shock limit, $p_2/p_1$ will approach 6 at its peak value (and across the entire face of the reflected shock immediately after the encounter). This is enough to explain the high pressure inferred for XA. For this case, $M_r = 2.24$, $p_2/p_1 = 2.5$, and $T_2/T_1 = 2.4$. Ignoring the effect of $T$ (this is not a terrible approximation), the density enhancement alone gives an increase in the volume emissivity of a factor of 6.25 over the material behind the adiabatic blast. Due to the steep ($T^{5/2}$) temperature dependence of evaporative mass loss, evaporation into region 2 would, in the absence of a
strong magnetic field, also be enhanced (by a factor of > 5) and could further contribute to the X-ray emissivity.

If the medium around the cloud were already somewhat denser than average (as discussed in subsection i) then the enhancement over the average X-ray emissivity will be larger. For example, if the material behind the blast wave in the vicinity of the cloud were about twice as dense and half as hot as average, then the reflected shock would heat it up to the "average" temperature of \(2 \times 10^6\) K. The density behind the reflected shock would be six times the average behind the blast wave, and the volume emissivity would be 36 times greater. The emissivity would be greater still if the pressure in region 1 were already higher than average (as discussed in subsection ii).

The early phase during which \(p_2/p_1 = 6\) across the face of the cloud will last a time comparable to that taken by the blast wave to pass the cloud. If the clouds are large, this will be long compared to a cooling time (for \(R_c = 1\) pc and \(v_b = 400\) km s\(^{-1}\), \(R_c/v_b = 2.5 \times 10^3\) years), so this situation should still apply to regions such as XA where much of the optical emission is younger than a cooling time (certainly < 10\(^3\) years). In Section III.D we also argued that on the north side of the region we can identify the point at which the blast wave is attached to the cloud.

The geometry and the nature of the emission at XA is consistent with a zone of emission behind a reflected shock.
The peak X-ray emission occurs at the nose of the cloud (where the pressure is the greatest) and tapers off to the north as the edge of the emission turns east (i.e., where the blast wave wraps around the edge of the cloud and the pressure needed to divert the flow is lower). Early on the reflected shock has a velocity of $1/2 v_s$ with respect to the cloud (e.g., Spitzer, 1982). The apparent thickness of the zone of X-ray emission ($\lesssim 0.2$ pc) requires that the plane of the unimpeded blast wave be $\lesssim 0.4$ pc east of the optical emission. This is about equal to the E-W separation ($\sim 0.35$ pc) between the optical emission at XA and the point at the end of the arc between XA and XB where the blast wave currently intersects the cloud. The larger indentation in the X-ray shell at XA must largely be due to the encounter with the denser envelope around the cloud. The time since the encounter inferred from the geometry ($0.35$ pc/400 km s$^{-1}$ $\lesssim 900$ years) is somewhat longer than expected based on emission type, although not disturbingly so. The geometry is not idealized, and if $0.07$ pc is taken as the thickness for the zone behind the reflected shock then the inferred time since the encounter drops to $\sim 350$ years. Also, since the time needed for the gas to radiate its thermal energy really varies as $T/n \propto p/n^2$, the higher pressure driving the radiative shocks will result in a longer cooling time. If the bright zone is approximately tangential to the line of
sight then the line-of-sight depth of the thin emitting region will be \( \sim R_c \).

After the blast wave has passed, the reflected shock will move away from the cloud, form a "steady state" bow shock for a time, and eventually dissipate. If the stagnation pressure \( p_3 \) is taken as characteristic of the bow shock region then \( p_3/p_1 = 2 \) and the X-ray emissivity will be no more than a factor of 4 higher than average. This could explain the lack of strong X-ray emission from HPD's much older Region III. At its projected distance behind the edge of the shell the reflected shock should no longer be as strong. The shape of the locus of optical emission also suggests a pointed intrusion into the shell. This shape (which could result from the action of the shock itself) would not impede the flow as much as a blunt cloud like the one at XA, and hence would not have as much of an effect on the X-ray emission. A similar argument can account for the lack of X-ray emission associated with the horizontal bar across the center of the field.

The idealized description presented here shows that the enhancement of X-ray emission to be expected as a result of the strong inertial compression needed to divert the hot flow around large clouds is adequate to account for exceptionally bright regions such as XA. This picture also satisfies the morphological characteristics of the X-ray emission and its relation to the optical structure.
The details of the geometry of the cloud and the flow around it provide other opportunities for inertial compression of the hot plasma. Calculations of radiation-driven implosions of clouds by Sandford, Whitaker, and Klein (1982, 1983) show many "hot spots" across the face of the cloud where there are significant transient increases in the pressure. A similar phenomenon might be expected to occur in the present case. Focussing of shocks or funneling of the hot flow may also occur. As noted above, the brightest knot in XA is located at an exterior corner in the X-ray contours above about .05 counts arcmin$^{-2}$ s$^{-1}$. Flow into a cavity of this shape could be geometrically compressed.

E. The ISM Around the Cygnus Loop

We have concluded that the brightest X-ray emission around the rim of the Cygnus Loop is due to the presence of large clouds and extended regions of higher than average density. It might still be possible to claim that the emission from the "unbrightened" portion of the shell is due to evaporation of clouds behind a faster shock, but the smooth nature of the X-ray shell would require that a model similar to the "small cloudlet picture" be invoked for the low density phase. A much more plausible explanation is that most of the shell is expanding into an ionized medium with a fairly uniform density of $\sim .1$ cm$^{-3}$ (similar to but
somewhat less dense than the "warm ionized medium" from McKee and Ostriker (1977). Embedded in this medium are HI clouds much like standard diffuse (and perhaps also large) clouds discussed by Spitzer (1978, 1985), as well as a less dense, partially neutral component similar to the "warm neutral medium" from McKee and Ostriker or the "not strongly absorbing" material from the 21-cm study of Payne, Salpeter, and Terzian (1983). The only evidence for the presence of a very diffuse "hot ionized medium" around the exterior of the Loop is the break-out in the south. As noted by KKPL, this looks much as expected for a break-through into a "tunnel" as described by Cox and Smith (1974).

The idea that the X-ray shell of the Cygnus Loop is due to an adiabatic blast wave expanding into a smooth medium is by no means new. (In fact, it is precisely the conception used when fitting the data to a Sedov solution to determine rms conditions around the Loop.) What has not been emphasized by previous authors, however, is the degree to which the observations confront various models of the ISM and SNR evolution.

The ISM around that Cygnus Loop does not appear to be the McKee and Ostriker ISM. Nor is the description of the Cygnus Loop in the preceding sections that of an evaporative SNR as described by McKee and Cowie (1975) and Cowie, McKee, and Ostriker (1981). We find that the inhomogeneity of the ISM affects the radiative cooling of the interior of the
remnant in ways not addressed by the models. We also find a lack of observational evidence to suggest that evaporation is as important a process as assumed by the models (at least for the Cygnus Loop).

V. Summary

We have presented a comparison at a resolution of 17" between optical emission from [O III] and [S II] and the thermal X-ray emission for a field on the SE edge of the Cygnus Loop SNR. The optical lines used represent emission from two ionic species found in extreme portions of the cooling regions behind radiative shocks. As expected (given the fact that the emission comes from physically different media), no one to one correlation is found to exist across the field. Two extended regions of bright X-ray emission are associated with optical emission, however. The edge of the region of brightest X-ray emission is coincident with the leading edge of the optical emission to within the alignment uncertainty and resolution of the data over a length of several minutes of arc. In this region the spatial relationship between the X-ray and optical emission is consistent with X-ray emission coming from a thin (~2 pc thick) zone located immediately behind the much thinner sheet-like locus of optical emission. At this location the data do not suggest that the optical filaments have been
engulfed by the blast wave. We believe that this conclusion can be generalized to most of the optical emission in the Loop.

Several possible explanations for the brighter than average X-ray emission in the vicinity of the optical emission are discussed. Cloud evaporation (which has been the favored mechanism for explaining the gross correlation between optical and X-ray emission in the Cygnus Loop and other similar SNRs) has a number of problems: (1) The contrast between regions of enhanced and unenhanced emission is too great to be easily explained by evaporation alone. (2) The small clouds required by some formulations of the evaporative picture do not lead to the observed optical morphology. (3) The detailed coincidence of X-ray and optical emission along a parsec-long edge is difficult to explain, due to differences in the time scales for evaporation and cooling. (4) There is no X-ray enhancement associated with a large cloud which should have had time to undergo significant evaporation. (5) There is strong X-ray emission from regions (such as the X-ray bright NE limb) where the optical data do not show the presence of clouds.

The physical picture which we find best fits the data is a multiphased ISM with large ($R_c \gtrsim 1$ pc) clouds immersed in a lower density "intercloud" medium which is somewhat denser near the clouds than elsewhere. (With the possible exception of the break-out in the south, this intercloud
medium is not the "hot ionized medium" which is the dominant phase of the McKee and Ostriker ISM.) Bright X-ray emission not locally associated with optical emission is explained by the extension of the denser intercloud medium beyond the cloudy regions. The X-ray emission from such regions will be brighter due to the higher preshock density, and will be further enhanced by inertial compression associated with deceleration of the blast wave as it runs up the density gradient. These mechanisms also apply in the immediate vicinity of the optical emission, where reflected shocks behind large clouds can account for the detailed coincidence of the brightest X-ray emission with optical features.

We feel secure in the conclusion that the "small cloudlet" picture of the Cygnus Loop is not viable. The discussion of evaporation as it applies to large clouds could be altered by time dependent calculations of the early phases of evaporation. Regions of higher than average X-ray emissivity will occur as a result of variations in the preshock intercloud density and dynamical compression of material behind the blast wave. Even in the absence of evaporation these effects appear to be adequate to explain the higher pressure and volume emissivity inferred in Section III for the bright X-ray regions. More work, both observational and theoretical, is needed to clarify the relative importance of these effects and thermal evaporation for the Cygnus Loop and other SNRs.
TABLE 2.1

Average Temperature of an Evaporative Flow

\[
\langle T_6 \rangle = \frac{\int_{R_C}^R \frac{T}{10^6 K} L(T) n^2(T, T_f) dV}{\int_{R_C}^R L(T) n^2(T, T_f) dV}
\]

<table>
<thead>
<tr>
<th>T_{6f}</th>
</tr>
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<tbody>
<tr>
<td>R</td>
</tr>
<tr>
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</tr>
<tr>
<td>2R_C</td>
</tr>
<tr>
<td>3R_C</td>
</tr>
<tr>
<td>4R_C</td>
</tr>
</tbody>
</table>

TABLE 2.2

Properties Across Bow Shocks Around Spherical Clouds

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<th>5.00</th>
<th>-</th>
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<td>P_2/P_1</td>
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<tr>
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<td>1.00</td>
<td>1.59</td>
<td>2.72</td>
<td>3.15</td>
</tr>
</tbody>
</table>
FIGURE CAPTIONS

Figure 2.1. Linear gray scale map of the soft X-ray emission from a field on the SE edge of the Cygnus Loop. The map is a composite of 2 Einstein HRI images provided by William Ku. The data have been smoothed by convolution with a Gaussian with FWHM = 17" in order to generate relatively smooth surface brightness contours from the counting statistics of the HRI data. The brightest knot has a surface brightness of .17 counts arcmin$^{-2}$ s$^{-1}$. The faintest regions on the east side of the field have an average surface brightness of .01 counts arcmin$^{-2}$ s$^{-1}$.

Figure 2.2. Linear gray scale maps of the optical emission from the 18' diameter central region of the field shown in Figure 1. The maps were generated from image tube plates taken with the CITD camera on the No. 1 91 cm telescope at KPNO. They show emission from [O III] $\lambda$5007 (Fig. 2a) and [S II] $\lambda\lambda$6725 (Fig. 2b). The stars have been suppressed and the noise has been reduced by 2σ rejection of pixels over a 3 X 3 pixel window. North is to the top of the figure and east is to the left. The scale is given by the bar at the top of the figure, which has a length of 5'.

Figure 2.3. Logarithmic surface brightness contours for [O III] (Fig. 3a) and [S II] (Fig. 3b) overlaid onto the X-
ray map shown in Fig. 2. The optical rasters were smoothed by convolution with a 17" FWHM Gaussian to match the resolution of the X-ray map before the contours were generated. The contours can be easily interpreted by comparison with Figure 2. Stars were suppressed before the smoothing so that starlight would not contaminate the nebular contours. The separation between contour levels is a factor of 2.

Figure 2.4. Schematic drawing of the field studied, with features and regions labeled for discussion.

Figure 2.5. Enlargement of the X-ray region XA. Figure 5a is a linear gray scale map of the smoothed X-ray emission, overlaid with logarithmic X-ray contours. The lowest contour level is 0.035 counts arcmin$^{-2}$ s$^{-1}$, and each contour is separated from its neighbors by a factor of $2^{1/2}$. Figure 5b shows these same contours overlaid onto a logarithmic gray scale map of the unsmoothed [O III] emission. A logarithmic gray scale was used so that both the faint and bright optical structure would be visible. The most remarkable detailed correlation between the optical and X-ray emission occurs along the eastern edge of the region.

Figure 2.6. Plots of the total X-ray emission internal to a given radius around an evaporating cloud, normalized to
the emission expected from the same volume of intercloud medium in the absence of evaporation. The plots take into consideration the fact that the cloud is a "hole" in the X-ray emission. L(T) is X-ray emissivity (ergs cm$^3$ s$^{-1}$) calculated from models by Raymond and Smith (1977). The evaporative profile was taken from Cowie and McKee (1977). Pressure equilibrium was assumed.

Figure 2.7. Sketches showing the geometry and labeling for an encounter between a blast wave and a spherical cloud. Fig. 7a shows the reflected shock shortly after its formation, before the cloud has been passed by the blast wave. (It is suggested in the text that this is the situation at the bright X-ray region XA.) Fig. 7b shows the steady state bow shock around the cloud sitting in the flow behind the adiabatic blast wave. The standard subscripts 0, 1, 2, and 3 refer to conditions ahead of the blast wave, behind the blast wave, behind the reflected shock, and in the cloud, respectively. The subscript 3 refers to conditions at the stagnation point at the nose of the cloud. X-ray emission should increase across the reflected shock, where the material behind the blast wave, already heated to X-ray temperatures, is subjected to further heating and compression.
Figure 2.4
Figure 2.6
CHAPTER 3

[O III] TEMPERATURE MAP OF THE CYGNUS LOOP SE

I. Introduction

The bright optical emission from the Cygnus Loop supernova remnant (SNR) is due to radiative shocks with \( v = 100 \text{ km s}^{-1} \) which are driven into interstellar clouds of density \( \sim 10 \text{ cm}^{-3} \) by an expanding supernova blast wave (McKee and Cowie 1975; Bychkov and Pikel'ner 1975).

Spectrophotometry of the Cygnus Loop has generally yielded [O III] electron temperatures (as inferred from the \( \lambda \lambda 4959,5007/\lambda 4363 \) ratio) between about 20,000 K and 45,000 K (Parker 1969; Miller 1974) although values approaching 70,000 K have been observed (Fesen, Blair, and Kirshner 1982). Similar values have also been observed in other middle aged SNRs such as Vela (Osterbrock and Costero 1973; Danziger and Goss 1982) and IC 443 (Fesen and Kirshner 1980). Electron temperatures as inferred from other ions ([N II], [O II], and [S II]), however, are generally observed to lie in the range of 10,000 K to 15,000 K (Miller 1974; Fesen, Blair, and Kirshner 1982). Both the magnitudes of these values and the difference in inferred temperature
among various ions are generally consistent with emission from a cooling flow behind a radiative shock.

While the variations in observed [O III] temperatures are significant, and the highest values appear to be somewhat at odds with models of the emission from steady flow shocks (e.g., Raymond 1979), little real insight into the properties of the shocks has been gained from the temperature observations. In part, this is because the [O III] temperature has not been found to correlate with other diagnostic line ratios such as [O III]/Hβ for positions across the Loop (Fesen, Blair, and Kirshner 1982).

Hester, Parker, and Dufour (1983), hereafter referred to as HPD, used a different technique to study correlations and spatial variations of line ratios for a field on the SE edge of the Cygnus Loop. They obtained images in the light of emission from six different ions, calibrated the images using the results of spectrophotometry, and produced two dimensional maps of a number of spectral line ratios. This technique allowed them to investigate the faint emission between bright filaments and to understand the relationship between the spectral properties of features and their morphology. In the present paper we extend their technique (as well as the framework of their interpretation) to the study of the spatial structure of the [O III] electron temperature.
In Section II the data are presented, and the reduction procedures and uncertainties in the results are discussed. In Section III the results are presented and shown to relate to the scheme for classifying features proposed by HPD. In Section IV a physical interpretation is offered based on the expected rise of the inferred electron temperature for shock velocities $> 120$ km s$^{-1}$ and the effects of extreme nonsteady flow on the [O III] emitting zone. Section V is a brief summary of the conclusions.

II. Data and Reductions

A. Observations and Processing of Surface Brightness Rasters

A field $\sim 18'$ in diameter located on the SE edge of the bright optical rim of the Cygnus Loop was imaged through filters which isolate emission from [O III] $\lambda 4363$ and [O III] $\lambda 5007$. The field observed is essentially the same as that discussed by HPD. The observations were obtained using the Carnegie Image Tube Direct camera at f/7.5 on the No. 1 0.9-m telescope at Kitt Peak National Observatory. The CITD camera uses an RCA 33063 two-stage image tube, with the output phosphor imaged onto baked IIIa-J plates. The filter characteristics and exposure times are given in Table 1.
The 4363Å filter used was narrow enough to separate [O III] emission from Hγ at 4340Å, even in an f/7.5 beam. To verify this, the 4363Å plate was carefully compared with the 5007Å plate and an Hβ image. The morphological differences between [O III] and Balmer line emission are such that any significant contamination would have been easily detected; no contamination was found. The 5007Å plate was taken immediately following the 4363Å plate, so the two plates were well matched both in terms of the placement of the image on the tube and the seeing conditions.

The plates were scanned in 20 µm (= .61 arcsecond) square pixels using the PDS microdensitometer at the University of Texas. This pixel size oversamples the ~30 µm resolution of the image tube, so significant averaging of plate transmittance did not occur. The characteristic curve relating photographic densities to an arbitrary linear intensity scale was calibrated for each plate using sensitizer plates which were exposed, developed, and scanned along with the image tube plates. The peak density of nebular emission on the plates was low enough (< 3.5) that saturation was not a problem. Approximately 50 star positions were measured in each raster and a 12 parameter 2-D mapping between the rasters was derived using a least squares fit. The rms residual to the fit was .15 pixel. This mapping was then used to transform the 4363Å raster
onto the nonastrometric coordinate system defined by the
5007Å raster. This procedure was used to correct for offset
and alignment errors in the way that the plates were scanned
and for slight differences in the images due to the
different characteristics of the two filters.

Because of the low surface brightness of λ4363 it was
necessary to work to reduce the pixel by pixel noise in the
rasters as much as possible before calculation of
temperatures from the data. The rasters were first filtered
by rejecting pixels > 2σ from the mean of the surrounding 7
× 7 pixel window, and replacing the rejected pixels with the
average of the surrounding 3 × 3 pixel window. The rasters
were then smoothed by convolution with a Gaussian
distribution with a FWHM of 6 pixels. The magnitude of the
noise in the surface brightness was decreased by a factor of
~ 6 by this process, while the resolution was degraded to ~
5". Filtering and smoothing reduced the small scale noise
in the log of the ratio of the two rasters to significantly
less than .05. This is somewhat less than the pixel to pixel
noise in the Hα/Hß ratio obtained by HPD using similar (but
less drastically smoothed) data, and should be
characteristic of the statistical error in the data
resulting primarily from the inhomogeneity of the image
tube.

An average background value was determined for each
raster by measuring several locations which were apparently
free of nebular emission, and the appropriate value was
subtracted from each raster. Severe variations in the
thermal background of the image tube were present across the
southern and western part of the field. These restricted
the useful portion of the weak, long exposure 4363Å plate.
Background subtraction was optimized for the center of the
portion of the field discussed by HPD, and further work
focussed there. This region was selected because it had the
most uniform background and because it allowed comparison
with the earlier work. Figure 1 shows the 5007Å and 4363Å
maps of the final field, which is about 9′.5 (~2.5 pc at the
canonical distance to the Loop of 770 pc — Minkowski 1958)
on a side. (Images were also obtained of the vicinity of
Miller’s 1974 position 3 on the west limb of the Loop.
These are not presented here because for that field the
greatest background variations across the tube happened to
fall along the filaments.)

Calibration of the ratio of the two rasters was
achieved by comparison of the rasters with unpublished
spectrophotometry of four positions in the field obtained by
the author in August 1983 using the IIDS spectrograph on the
2.1-m telescope at KPNO. These spectra were calibrated
using the standard IDS reduction routines at Kitt Peak. The
Hg λ4358 night sky line was typically about as strong as
λ4363, but sky subtraction completely removed the far
stronger [O I] λ5577 line, as well as other lines of Hg, so
\( \lambda 4358 \) did not affect the measurements. The \([\text{O III}] \lambda 4363\) and \(H_\gamma \lambda 4340\) lines were very slightly convolved in the spectra, so the line strengths were measured by fitting two Gaussian profiles and a linear background to the two lines and the surrounding continuum. A reddening of \( E(B-V) = 0.08 \) was assumed (Parker 1967).

B. Generation of the Electron Temperature Map

For \( \text{O}^{++} \), the ratio of the auroral to the transauroral lines is sensitive to the electron temperature. For conditions in the Cygnus Loop the density is much less than the critical density for collisional deexcitation of the \(^1S\) and \(^1D\) excited states. [Observations yield \( n_e < 1000 \text{ cm}^{-3} \) in the denser \([\text{O II}]\) and \([\text{S II}]\) emitting zones (e.g., Parker 1964; Fesen, Blair, and Kirshner 1982).] In this case, the relationship between the temperature and the line ratio becomes independent of density. If population of the \(^1S\) level by collisional excitation from the \(^1D\) level and population of the \(^1D\) level by radiative decay of the \(^1S\) level are neglected, then the ratio

\[
R = \frac{J_{4959} + J_{5007}}{J_{4363}}
\]

is given (e.g., Osterbrock 1974) by

\[
R = \frac{T^{(3P,1D)}}{T^{(3P,1S)}} \left[ \frac{A^{1S,1D} + A^{1S,3P}}{A^{1S,1D}} \right] \frac{\nu^{(3P,1D)}}{\nu^{(1S,1D)}} e^{\Delta E/kT_e}
\]

(2)
where $v(\text{P}^3, 1D)$ is the average frequency of $\lambda \lambda 4959, 5007$, weighted according to the transition probabilities, and $\Delta E$ is the separation energy between the $1S$ and $1D$ states. Using transition probabilities from Nussbaumer and Storey (1981) and collision strengths from Baluja et al. (1980, 1981) (as tabulated by Mendoza 1983) and inverting gives

$$T_e = \frac{3.296 \times 10^4}{\ln(R) - 2.013} \text{ K.}$$

The 5007Å raster was multiplied by 4/3 to obtain the total surface brightness for radiation from the $1D \rightarrow 3P$ transition. Before computation of pixel by pixel line ratios, a floor was assigned to each raster, below which pixel values were judged to be too low for confident generation of ratios. These floors were assigned so that at the lowest surface brightnesses used the noise in a raster did not result in errors in the ratio of significantly greater than 15%. (These floors also restrict the data used to values on the linear part of the photographic characteristic curve.) In the western part of the field the background of the 4363Å raster was ~ 50% of the assigned floor. A map of the electron temperature in the O$$^+$ zone was generated using the value of $R$ for each pixel with surface brightnesses above the assigned floors.
Figure 2 shows a gray scale representation of the map of the log of the inferred electron temperatures. The grey scale covers a range of $\log(T_e)$ from $\sim 4.2$ to $4.7$ (15,000 K to 54,000 K), with the lightest areas being the hottest and the darkest areas being the coolest. The sharp edge which delineates the regions of nebular emission is determined predominately by the level at which the surface brightness of the 4363Å raster dropped below its assigned floor.

C. Uncertainties

There are four sources of uncertainty in the determination of the value of $T_e$ for a given pixel. The first of these is noise in the line ratio. An uncertainty of $\Delta \log R = \pm 0.05$ corresponds to an uncertainty in the temperature of $\Delta T_e/T_e^2 \approx 3.5 \times 10^{-6}$. At $T_e = 30,000$ K, this gives $\Delta T = 3200$ K. For a region or feature with extension $>> 5''$, the determination of the average temperature improves with the square root of the number of $\sim 20$ arcsec$^2$ resolution elements sampled. This makes it possible to confidently distinguish a distinct feature from surrounding emission which differs in $T_e$ by only a few thousand degrees.

The second source of uncertainty is large scale variations in the background intensity across the field. This background is due both to the thermal background of the tube and the presence of Hg $\lambda 4358$ in the night sky spectrum.
For a given part of the plate, this introduces an error in the temperature determination which is dependent on the surface brightness. For most of the field the variations in the background are < 10% of the signal, and the associated error in the temperature is about 2500 K. In the western part of the 4363Å raster the high background amounts to about 50% of the assigned floor value. For temperatures around 30,000 K, this translates into an error of about 11,000 K for emission with a surface brightness just above the floor, and ~ 3000 K for bright emission. The "hot" edge surrounding the region of emission on the right hand side of Figure 2 is an artifact of the high background there. The absence of such edges and the lack of a strong correlation between surface brightness and log(T_e) elsewhere in the field supports the conclusion that the background is not a major source of error except in the west.

A third possible source of uncertainty involves "color" terms due to large scale wavelength dependent variations in sensitivity across the face of the photocathode, large scale variations in transmittance across the filters, and/or reddening variations. Using similar data, HPD found that the observed Hα/Hβ ratio varied by ~ 20% across the field. They could not unambiguously determine the source of the variation, although the trends in the spectra used to calibrate the present data support the hypothesis that the variation was largely real and due to variations in
reddening. Fesen, Blair, and Kirshner (1982) found evidence to support an additional color excess $E(B-V)$ of $0.05 - 0.10$ magnitudes for many positions in the Loop. A $\pm 10\%$ uncertainty in $H\alpha/H\beta$ due to reddening corresponds to an uncertainty of $\sim \pm 5\%$ in $\lambda 4363/\lambda 4959,5007$. If the total variation of $\sim 20\%$ in $H\alpha/H\beta$ is due to color dependent variations in the tube sensitivity, then the total variation in the relative sensitivity between the two lines of $[O III]$ (which are separated by $<650\ \text{Å}$ and lie in a fairly well behaved wavelength regime for an S-20 photocathode) should be $<10\%$. Unfortunately, little can be said in detail about the uniformity of the filters' transmittance other than to note that "image quality" filters are generally flat to within $10\%$ or so and that the field studied samples a fairly small area near the center of the filter.

A final source of uncertainty is the absolute calibration of the ratio of the two rasters. This is essentially a zero-point error, and does not significantly affect relative comparisons of the temperature across the field (at least for $T_e < 40,000\ \text{K}$). Of the four locations for which spectrophotometry was available, two lay along the "spur" (see HPD) located in the western part of the field where the high image tube background was a problem for the $4363\text{Å}$ plate. The normalization of the $4363\text{Å}$ raster to the photoelectric results was in fact a bit lower for these two locations, and so they were not used. Despite this
difficulty, the sample (i.e., n-l) rms scatter in the normalizations using all four observations was only 17%. The normalization obtained from the two calibration points used differed by 10%.

The uncertainties in the reddening mentioned above also affect the absolute calibration. Had the calibration been done by applying a reddening correction to the individual spectra assuming \( \text{H} \alpha/\text{H} \beta = 3 \), rather than \( E(B-V) = .08 \), \( \lambda 4363 \) would have been 11% higher relative to \( \lambda \lambda 4959,5007 \). This changes \( \ln(R) \) by .1, which would only increase a reported temperature of 30,000 K slightly (to 33,000 K), but would increase a reported temperature of 50,000 K to \( \sim 60,000 \) K. By using \( E(B-V) = 0.08 \), we avoid the regime where \( T_e \) varies critically with \( \ln(R) \) and hence avoid artificially producing very high temperatures. In so doing, however, we may significantly underestimate the temperature of the hottest features.

III. Results

HPD introduced the concept of feature "type" based on the presence or absence of a surface brightness feature in emission from different species. Briefly, type I features are those which appear in lines from species with a wide range of ionization potentials (e.g., \([\text{O I}], [\text{O II}], \) and \([\text{O III}]\)), while type II features appear only in lines from
high ionization species such as $O^{++}$. An intermediate class of feature, labelled type 1.5, are not seen in lines from the lowest ionization species such as [O I], but do appear at least weakly in [O II] and Hα. Comparison of Figure 2 with Figures 4-6 in HPD shows that there is a good correlation between feature type as defined by HPD and the electron temperature inferred from the [O III] line ratio.

The most striking aspect of Figure 2 is its lack of structure. The broad band of emission running from the upper left of the field down and across the center of the field (HPD's Region I) consists primarily of type I emission. Across the face of this region the inferred [O III] temperature lies in the range of 22,000 K to 30,000 K, with an average value of ~26,000 K. HPD reported that for type I features the diffuse emission between bright filaments was often spectrally similar to the filaments themselves. The current results show that bright filaments and the surrounding diffuse emission are generally not distinguished by temperature, either. (The unpublished data for the west limb of the Loop show the same to hold for that field.)

The filaments lying along the eastern edge of HPD's Region I and the southern edge of the horizontal bar across the center of the field were identified by HPD as type 1.5 and type II. These features are here observed to be marginally hotter than the type I emission, with a
temperature of $\sim 31,000 - 32,000$ K. A band $\sim 1'$ behind the leading edge also shows $T_e \approx 31,000$ K. This band is more like the leading edge in other respects as well. HPD concluded that it was type I.5 and fast type I emission seen in projection against the face of Region I. The region of bright [O III] emission in the SE corner of the field (which is also type I.5) has an average temperature of $\sim 30,000$ K and a temperature of $33,000$ K at its center. These regions all have exceptionally strong [O III] $\lambda 5007$/H$\alpha$ ($\gtrsim 6$). Significantly, while a feature can be seen in maps such as these to be somewhat hotter along its length than its surroundings, the difference in temperature of $\sim 4000$ K would be hidden in the noise in most spectrophotometric observations of a number of locations.

The isolated N-S arc extending below the SE corner of Region I was HPD's prototype for type II emission (see their Figure 14). This arc is the most extreme example found in the field of a feature which is seen only in emission from [O III]. It is also the only feature in the field with an inferred temperature significantly greater than $30,000$ K. The temperature along this feature varies a great deal, but the hotter parts clearly have inferred temperatures in the range of $40,000$ K to $50,000$ K, with a formal peak temperature of $52,400$ K near its northern end. (Nowhere along the feature does the inferred temperature drop below about $35,000$ K.) That this high temperature is real and not
a local effect as discussed in Section II can be seen by comparing the arc with surrounding features in the 4363Å and 5007Å maps in Figure 1. The arc is clearly brighter relative to its surroundings at 4363Å than at 5007Å (where it is hardly conspicuous at all).

Figure 3 shows the map of $\log(T_e)$ with 5 slices indicated. Each slice is 30" - 40" long, and so cuts through ~ 7 separate resolution elements. Each was positioned to lay along an area characteristic of the types of emission discussed above. Figure 4 shows temperature profiles along each of these positions. The vertical scale is linear in $\log(T_e)$, where $T_e$ is calculated assuming $E(B-V) = 0.08$. The scale on the right side of the figure gives the observed ratio, also corrected using $E(B-V) = 0.08$. These profiles show the reality of the temperature variations discussed. Positions 1 and 2 cut through regions of type I emission. They are both very flat, with a scatter of ± 2000 K. Had the slice along position 1 in particular been extended for ~ 2' further it would still have shown essentially no variations. Positions 3 and 4 lie along type I.5 filaments at the leading edge of the emission. The scatter along each profile is comparable with that along the profiles of type I emission, but the mean value is ~ 4000 - 5000 K higher. The slices at positions 2 and 3 are parallel to each other, and separated by only about 45", so the comparison between these two profiles is particularly
meaningful. Figure 5 shows surface brightness profiles and a temperature profile along position 3. The surface brightness varies by a factor of ~2 along this feature, and shows significant small scale structure. The temperature profile, on the other hand, is essentially flat, and shows no significant correlation with the surface brightness.

Position 5 lies along the northern end of the [O III] arc, and samples both the hottest and coolest parts of that feature. While at high temperatures the temperature determination is more sensitive to noise (see the scale on the right side of Figure 4) it is clear that temperatures along this slice are significantly hotter than the others. Figure 4 also shows the significance of the uncertainty in reddening. For the type I and I.5 emission, the higher reddening would make little real difference in the temperature determination, but for the extreme type II arc a higher reddening would imply peak temperatures in excess of 60,000 K.

The [O III] temperatures inferred from the imagery data lie within the range of temperatures reported for the Cygnus Loop by other authors (Miller 1974; Fesen, Blair, and Kirshner 1982). Fesen, Blair, and Kirshner reported temperatures ranging from 20,000 K ± 8000 K to 69,000 K ± 12,000 K for 11 positions across the Loop. The value of ~27,000 K reported here for the bulk of the emission is somewhat lower than their median temperature of 32,000 K ±
7000 K, although the disagreement is not serious.

Calibrating the rasters with a reddening correction assuming
$H\alpha/H\beta = 3$ would bring the current temperature determinations
into better statistical agreement with the previous results.
(This again is consistent with the claim that the
temperatures reported here are not overestimated, and that
the high temperature reported for the type II arc is not due
to a calibration error.) The difference in average
temperatures may also be real. HPD suggested that the
spectrophotometry presented by Fesen, Blair, and Kirshner
may suffer from selection effects favoring type I.5 and type
II features, which, at least for the field studied, appear
to be hotter than type I emission.

IV. DISCUSSION

A. The Nature of the Inferred Temperature

In the Cygnus Loop and other similar objects, emission
from species of differing ionization potentials arises as a
result of a cooling and recombining flow behind radiative
shocks. The temperature inferred from the [O III] line
ratio does not represent emission from a homogeneous region
with a well defined and uniform temperature. Rather, it is
an average temperature, weighted according to $n_e n_{O^{++}},$ over
the part of the flow where a significant fraction of the
oxygen is doubly ionized. At the hot end of the zone the actual temperature is due to the amount of heating in the shock (for slower shocks) or the temperature at which $O^{+3}$ recombines.

Most of the cooling in the portion of the flow with $T_e > 30,000$ K is provided by He II $\lambda$304. Cooling due to forbidden emission from [O III] is relatively unimportant for this region (e.g., Raymond 1979). The [O III] emission from the shock is dominated by the cool end of the $O^{++}$ zone where $O^+$ is photoionized by 304 Å photons. As a result, the inferred [O III] temperature is expected to be fairly constant. For example, for Raymond's (1979) models B through I (which have shock velocities ranging from 60 km s$^{-1}$ to 200 km s$^{-1}$, with little variation in other parameters) the temperature immediately behind the shock ranges from 69,000 K to 570,000 K, while the temperature inferred from the [O III] line ratio varies by less than a factor of 2 (from 24,000 K to 38,000 K).

B. Model Comparisons

Figure 6 shows a plot of inferred [O III] temperature versus shock velocity for a sample of published models. The capital letters refer to Raymond (1979). The lower case letters refer to Shull and McKee (1979). The numbers refer to members of shock "families" computed by Cox and Raymond
(1985). The bars on the right hand side of the figure indicate the range in temperature for the different classes of emission in the field. Raymond's "standard set" of models (B through I, connected by lines on the figure) will be used as a basis for comparison, with some consideration given to differences between the model sets.

The temperatures associated with type I emission lie in the range of Raymond's "standard set" of models with $60 \text{ km s}^{-1} \leq v_s \leq 120 \text{ km s}^{-1}$. This range of velocities agrees with that obtained for the type I emission in the field on the basis of other optical lines. The type I features closest to the eastern edge of Region I are strong in [O I] emission relative to other lines (see HPD, Figures 6 and 12). Comparison with model calculations shows this increase to occur for $v_s \gtrsim 100 \text{ km s}^{-1}$. For velocities less than this, [O III] $\lambda 5007$/H$\alpha$ becomes extremely sensitive to velocity. This ratio declines steadily to the west of the leading edge of the region to the point where [O III] emission becomes exceptionally weak. The lack of a similar decline in $T_e$ behind the leading edge is suggestive of Raymond’s models B-F, with $80 \text{ km s}^{-1} \leq v_s \leq 120 \text{ km s}^{-1}$. On the basis of all of their observed line ratios, HPD concluded that the shock velocity across this region drops from east to west from $\sim 100 \text{ km s}^{-1}$ to $\lesssim 70 \text{ km s}^{-1}$.

The temperatures inferred for the leading edge type I.5 - II emission match the models with $80 \text{ km s}^{-1} \leq v_s < 140 \text{ km}
s\(^{-1}\). More significantly, the increase in \(T_e\) of \(~4000 - 5000\) K relative to the neighboring type I emission agrees with the increase in temperature between the 120 km s\(^{-1}\) and 140 km s\(^{-1}\) models. This relative result is less dependent on the uncertainties in calibration, reddening, or model parameters. The higher temperatures at the leading edge are then probably a result of the higher velocity.

The 40,000 - 50,000 K temperatures associated with the extreme type II arc appear to be too high to be easily explained by emission from an integrated steady flow shock model. The only Raymond (1979) models with inferred [O III] temperatures greater than 37,000 K have full preionization of He to He\(^{++}\). There is no reason to expect that the preionization in this region should be significantly higher than elsewhere in the field. In fact, as discussed below, it is expected that the preionization is likely to be low rather than high due to the brief history of UV irradiation from the shock front (although the lack of H\(\alpha\) emission from the filament suggests that most of the hydrogen is ionized). In Raymond’s (1979) models, high velocity alone doesn’t give temperatures as high as 50,000 K. The 190 km s\(^{-1}\) and 200 km s\(^{-1}\) models from Cox and Raymond (1985) predict \(T_e \approx 50,000\) K, but shocks in the Cygnus Loop in excess of 150 km s\(^{-1}\) should not be in their radiative phase at all (e.g., Raymond et al. 1981, 1983). Deep optical and UV spectra of this arc
would be very useful in better determining the shock velocity and preionization.

C. Nonsteady Flow

Raymond et al. (1980a), Fesen, Blair, and Kirshner (1982), and other authors have argued that deviations from steady flow behind the shock front, and in particular incomplete cooling and recombination regions, may be responsible for various line ratios which cannot be accounted for by model calculations. HPD showed that their classification of feature type is related to the completeness of the cooling and recombination regions. Type I features are present in emission from lines formed in all parts of the cooling flow, and in general show line strengths which are consistent with steady flow model calculations. Type 1.5 and type II features are absent in lines formed in progressively warmer parts of the flow, and indicate that trailing portions of the cooling and recombination regions have not had a chance to form.

For example, when associated with type I features, the ratio of a line formed a short distance behind the shock to a line formed in the recombination zone is sensitive to shock velocity. As a result, [O III]/[O II] or [O III]/Hα are good velocity indicators in the range of 60 - 100 km s⁻¹. When associated with type II or type 1.5 features, on
the other hand, these ratios are dominated by the degree to
which the zone in which the cooler lines are formed is
incomplete.

1) Steady Flow Temperatures

The present observations indicate that nonsteady flow
features are generally hotter than steady flow features, and
that the higher temperatures could be explained by greater
shock velocities. For the leading edge type I.5-II features
there is additional evidence that the higher temperatures
are due to faster shocks. Although the strong [O III]/Hα
exhibited by these features is not itself a reliable
velocity indicator for the nonsteady flow emission,
geometrical extrapolation of the velocity gradient in the
type I emission suggests that the nonsteady flow shocks may
have $v_s \geq 120$ km s$^{-1}$. (It is somewhat fortuitous that for
the field studied the point at which [O III]/Hα becomes
insensitive to shock velocity happens to be about the
velocity of the observed transition between steady and
nonsteady flow.) In addition, using UV observations
(sensitive primarily to emission from the hot part of the
flow), Raymond et al. (1980a, 1981) obtained velocities of $\sim
130$ km s$^{-1}$ for two filaments which on the basis of optical
spectra (Miller 1974; Fesen, Blair, and Kirshner 1982)
appear to be incomplete cooling regions.
The association between nonsteady flow and large velocities is not hard to understand (HPD). Incomplete cooling regions must be very young, implying a recent encounter between the blast wave and the cloud. The shock is therefore likely to be moving into the less dense outer portions of the cloud, and may also be driven by a higher pressure associated with the bow shock of the cloud (e.g., McKee and Cowie 1975). As the shock moves into the denser part of the cloud and the overpressure dissipates, a shock with \( v_s \gtrsim 130 \text{ km s}^{-1} \) and an incompletely formed cooling region will evolve into a shock with \( v_s \lesssim 100 \text{ km s}^{-1} \) and completely formed cooling and recombination regions exhibiting roughly steady flow emission. In addition, the cooling time for material behind a shock increases as the density of the preshock medium decreases and the shock velocity increases, so it is the faster shocks which are more likely to be caught in their nonsteady flow phase.

The lack of observed temperatures below about 22,000 K is perhaps due to the very low intrinsic brightness of [O III] emission for slow shocks, especially when being driven into a largely neutral medium. The emission which was discarded when setting floors to assure good signal to noise generally had \([\text{O III}] \lambda 5007/\text{H}\alpha \lesssim 0.4\), which suggests shock velocities of \( \sim 60 - 80 \text{ km s}^{-1} \) or less. These are the shocks expected to produce the low temperature emission. Deep photoelectric observations of a few locations in this
diffuse emission are needed to investigate the behavior of the [O III] zone in the cooling flow behind these slower shocks.

II) The Hot Arc

As noted above, the high inferred temperature of the extreme type II arc cannot be explained using steady flow shock models. It can be explained, however, by extending the analysis of an incomplete cooling flow to the [O III] emitting zone of the cooling region, itself. The fact that the [O III] arc is absent in all other lines indicates that the regions downstream of the [O III] zone (in the frame of the shock) have not even begun to form, in which case the [O III] zone itself should be incomplete. The high inferred temperature is then due to the absence of the cooler end of the [O III] zone. This explanation is attractive because it does not require preshock conditions which are markedly different from the rest of the field, and because of the independent evidence suggesting that the recombination zone is absent.

III) Nonsteady Flow and High Temperatures

The suggestion that incomplete cooling regions are related to high inferred temperatures is not new. Raymond
et al. (1981) suggested that this may account for the high temperature of Miller's position 3. Fesen, Blair, and Kirshner (1982), on the other hand, found for 11 positions in the Loop that no general relationship exists between $T_e$ (as determined from the [O III] line ratio) and [O III]/Hβ. This lead them to reject the suggested relationship between $T_e$ and completeness of the cooling region.

The discrepancy between the present conclusion and that of Fesen, Blair, and Kirshner is probably due to their implicit assumption that [O III]/Hβ is a straightforward indicator of nonsteady flow. Confident judgments about the completeness of cooling regions can really only be made by morphological comparisons of the emission from a number of different species. (This again points out the need for caution in interpreting spectra without also considering available morphological information.)

Initially, if the aperture used for spectrophotometry integrates over a significant amount of structure, then [O III]/Hβ and $\lambda\lambda 4959,5007/\lambda 4363$ can be dominated by different positions along the slit. HPD showed, for example, that [O III]/[O I] varied by about a factor of 10 along the length of the slit at Miller's position 2, and that a significant amount of the emission from the cooler species came from a part of the slit where [O III] was quite weak. Furthermore, since near tangency of the shock front to the line of sight is required for the formation of bright
filaments (e.g., Parker 1967; Miller 1974; HPD; Hester 1985b), conditions may vary significantly along the large line of sight depth through a single feature. Spectrophotometry also provides no information about the degree to which foreground or background emission contribute to the spectrum. Type II [O III] features are sometimes seen to lie against a background of strong emission from cooler lines. In these instances emission from [O III] and Hβ come from physically unrelated regions, and [O III]/Hβ gives no true indication of the completeness of the cooling region behind the shock responsible for the [O III] emission.

There are also physical reasons why [O III]/Hβ is an unreliable indication of nonsteady flow. If a significant fraction of neutral H is present in the preshock gas, then there will be a strong collisional contribution to the Hβ flux originating immediately behind the shock front. This contribution can be comparable to or even stronger than the recombination portion of Hβ (e.g., Cox and Raymond 1985). The Balmer line filaments observed by Raymond et al. (1981, 1983) and Fesen and Itoh (1985) are very fast non-radiative shocks in which even the [O III] emitting region is essentially absent. The spectra of these features (which can be thought of as defining a "type III" in the continuum of feature types) are dominated by collisionally excited emission from HI before it is completely ionized (Chevalier
and Raymond 1978). In these features, [O III]/Hβ is exceedingly small, while the temperature of the emitting region exceeds \(4 \times 10^5\) K.

It is expected that the preshock neutral fraction will often be larger for type II emission. Early in the encounter of the shock wave with a cloud (when the cooling region is incomplete) the UV precursor of the shock will not have been able to ionize the preshock medium (J. Raymond 1984, private communication) and the collisional contribution to Hβ will be strong. For position X in Fesen, Blair, and Kirshner \(T_e = 65,000\) K ± 11,000 K), [N II] \(\lambda 6583/\text{Hα} = .375\). This is a factor of 2 lower than the average value of .78 ± .16 (rms scatter for positions for which [O III] temperatures were reported), and indicates a strong collisional contribution to the Balmer line emission.\(^{(1)}\)

The final point to be made when comparing the ratio of [O III] to a line formed in the recombination zone is that if the feature is present at all in the cooler line, then it indicates that the [O III] zone is substantially complete.

\(^{(1)}\) The fact that both the preshock neutral fraction and nonsteady flow can affect [N II]/Hα implies the need for caution when using this ratio as a diagnostic of the ionization state of the preshock gas as suggested by Cox and Raymond (1985).
and the [O III] temperature should reflect this fact. It is only in extreme type II features, where the recombination region has not even begun to form, that the [O III] zone itself may be sufficiently incomplete to affect the inferred $T_e$.

D. Other Model Sets

Raymond's (1979) models were used almost exclusively in the comparisons above, and indeed the general range of observed temperatures (both here and elsewhere in the Loop -- Fesen, Blair, and Kirshner 1982) agrees best with this set of models. Shull and McKee (1979) generally predict inferred [O III] temperatures which are somewhat lower than Raymond's. The temperatures inferred for steady flow emission tend to lie between Raymond's models with $80 \text{ km s}^{-1} \leq v_s \leq 120 \text{ km s}^{-1}$ and Shull and McKee's models with $90 \text{ km s}^{-1} \leq v_s \leq 130 \text{ km s}^{-1}$. HPD found that for this field, variations in most line ratios lie within the general domain defined by these two sets of models.

The models from Cox and Raymond (1985) predict temperatures which are significantly higher than the earlier models. This seems to be due primarily to the inclusion of charge exchange in the model code (Butler and Raymond 1980). Charge exchange has the effect of driving $O^{++}$ to $O^+$ at a higher temperature. There is some reason for caution in
applying this result, however. The new models are in somewhat worse agreement with the observations than the earlier models, and the ratio $\lambda\lambda 4959,5007/\lambda 4363$ reported by Butler and Raymond for their 120 km s$^{-1}$ model ($R = 4.8$) is significantly below the $T + = \infty$ limit of equation (2). [The ratio reported in the absence of charge exchange was also too small ($\approx 6$) and the error was probably due to a defect in the forbidden line subroutine in the code which has since been corrected (J. Raymond 1985, private communication).] In addition, it seems likely that errors remain in the charge exchange rates, many of which have only recently become available.

These difficulties notwithstanding, if a real discrepancy exists between the observed ratio and what should be produced by steady flow shocks, it could perhaps indicate that thermal instabilities (e.g., McCray, Stein, and Kafatos 1975; Chevalier and Imamura 1982) are important in the cooling region.

V. Summary and Concluding Remarks

A map of the electron temperature inferred from the ratio of [O III]$\lambda\lambda 4959,5007$ to [O III]$\lambda 4363$ is presented for a field on the SE edge of the Cygnus Loop SNR. Feature "type" as defined by comparing the morphology of emission from a number of ions is found to be related to inferred
[O III] temperature. For feature types 1 and 1.5 the recombination zone is present, at least in part, and the [O III] zone can be assumed to be complete. For this emission the inferred temperatures are consistent with integrated steady flow shock models having $60 \text{ km s}^{-1} \leq v_s \leq 140 \text{ km s}^{-1}$ and little preionization of helium to He$^{++}$. These velocities, as well as the trend for shocks at the upper end of this range to be associated with nonsteady flow emission, generally agrees with results determined from other optical and UV studies.

A $T_e$ of $\sim 40,000 - 50,000$ K is inferred for an extreme type II feature. This temperature is too high to be easily accounted for by steady flow models with parameters which are plausible for the Cygnus Loop. For this feature the absence of emission from species cooler than O$^{++}$ indicates that the recombination region hasn’t even begun to form. The high $T_e$ further indicates that only the hotter portions of the [O III] zone are present.
### TABLE 3.1

**Filter and Exposure Data**

**Filter**

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<th>Plate #</th>
<th>Central $\lambda$</th>
<th>FWHM</th>
<th>Exposure</th>
</tr>
</thead>
<tbody>
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<td>4363 A</td>
<td>15 A</td>
<td>90 min.</td>
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<tr>
<td>5841</td>
<td>5007 A</td>
<td>22 A</td>
<td>31 min.</td>
</tr>
</tbody>
</table>
FIGURE CAPTIONS

Figure 3.1. Linear gray scale surface brightness maps of a field in the SE Cygnus Loop SNR taken in the light of [O III] \( \lambda 5007 \) (Fig. 1a) and [O III] \( \lambda 4363 \) (Fig. 1b). The field in \( \sim 9'\).5 on a side (\( \simeq 2.1 \) pc at the canonical distance to the Loop of 770 pc). The maps show the surface brightness rasters after sky subtraction but before a floor was assigned to each. The histogram accompanying each figure shows log(number of pixels) for each of the 128 gray levels. The labels on the gray scales are arbitrary.

Figure 3.2. A map of the log of the electron temperature, as inferred from \( I(\lambda 4959,5007)/I(\lambda 4363) \), for the field shown in Figure 1. Pixels for which \( I(\lambda 4363) \) was too low for generation of a reliable ratio are shown as black. The gray scale extends from about 16,000 K to 54,000 K.

Figure 3.3. The map of \( \log(T_e) \) with the positions of slices marked.

Figure 3.4. \( T_e \) profiles along the positions marked in Figure 3. Each slice is 30" - 40" long. The scale is linear in \( \log(T_e) \), where \( T_e \) is calculated using the average reddening of \( E(B-V) = 0.08 \) for the Cygnus Loop determined by Parker (1967). The scale is also calibrated in \( T_e \).
calculated using a reddening correction determined for the field by assuming $\frac{H\alpha}{H\beta} = 3$. The scale on the right shows the line ratio, also corrected assuming Parker's average reddening.

Figure 3.5. $T_e$ and surface brightness profiles along position 3 shown in Figure 3.

Figure 3.6. Inferred [O III] electron temperatures predicted by shock model calculations plotted against shock velocity. The capital letters refer to Raymond (1979). Models B-1 form a "standard set" of models with $n_0 = 10 \text{ cm}^{-3}$ and fairly uniform preshock conditions. The lower case letters refer to Shull and McKee (1979). Their models c-g also form a set of $n_0 = 10 \text{ cm}^{-3}$ models, but with equilibrium assumed between the preshock ionization and the UV radiation field of the shock. The numbers refer to Cox and Raymond (1985). The bars on the right side of the figure indicate the range of the observed temperature for various feature types. The figure is also labelled with the observed line ratio.
Figure 3.4
Figure 3.5
Figure 3.6
CHAPTER 4

A SHEET MODEL FOR THE CYGNUS LOOP

I. Introduction

Middle aged supernova remnants (SNRs) such as the Cygnus Loop, Vela, and IC 443 have been studied by a number of authors in a variety of wavelength regimes over the course of the last few decades. The general consensus is that these objects represent expanding supernova blast waves, still in their adiabatic phase of evolution, which drive slower radiative shocks into clouds in the ambient interstellar medium (ISM) (McKee and Cowie 1975; Bychkov and Pikel’ner 1975).

Various pictures have been put forward to explain different observations of SNRs such as the Cygnus Loop. Small cloudlets of various types have been suggested to account for spatial variations in the spectral properties of the optical emission (Fesen, Blair, and Kirshner 1982), observations of X-ray and coronal line emission (e.g., Ku et al. 1984; Teske and Kirshner 1984), and the kinematic structure of filaments (Shull, Parker, Gull, and Dufour 1982, hereafter SPGD). Rope-like structures have been used
as an explanation for the observed filaments (e.g., Dickel and Willis 1980), which can have lengths up to several parsecs. These ropes are supposed either to preexist in the ambient ISM or form behind the shock front as a result of thermally unstable collapse perpendicular to field lines (McCray, Stein, and Schwarz 1972; Duin and van der Laan 1975), and may be flattened by the action of the shock front (Smith and Dickel 1983).

Radio observations of the HI around the Cygnus Loop, on the other hand, support the existence of larger clouds ($N_H \approx 1-2 \times 10^{20} \text{ cm}^{-2}$, $R_C \approx 5 \text{ pc} \Rightarrow n_C \approx 5-10 \text{ cm}^{-3}$) lying just outside the bright optical filaments (DeNoyer 1975). This column density is about average for interstellar clouds (e.g., Dickey, Salpeter, and Terzian 1978; Hobbs 1974). A molecular cloud is seen just west of the Loop (Scoville et al. 1977) and the edge of the western limb of the Loop is coincident with a lane of absorption. The structure of the ISM supposed by the small cloud view differs from that inferred from 21 cm investigations of the structure of the ISM. These studies generally indicate that HI clouds are fairly smooth on small scales (e.g., Payne, Salpeter, and Terzian 1983). Hester and Cox (1985) outlined a variety of other arguments against the small cloud view.

The lack of a unified description of middle-aged SNRs limits the contribution to the understanding of the structure of the ISM and the physics of interstellar shock
waves arising from the study of these objects. Perhaps the most simpleminded view of the blast wave/cloud interaction in middle-aged SNRs would suppose that the blast wave itself, upon entering an extended region of sufficiently high density (i.e., upon encountering a cloud such as those inferred from the radio data) would slow to become a large scale sheet-like radiative shock (Poveda and Woltjer 1968). Sofue (1978) gives a very convincing presentation of how such a geometry applies to the old remnant S147. In the present paper, this "simple" view involving large clouds and extensive sheet-like radiative shock fronts will be shown to provide a framework in which the interpret virtually all of the observations of the Cygnus Loop. (In doing so, we will in a sense come full circle back to a picture resembling that held over a decade ago, but with a much clearer understanding of the implications and limitations of that view.) Section II presents models of the surface brightness and velocity profiles resulting from projected thin sheets. Section III presents the application of the sheet model to published observations of the Cygnus Loop. Section IV contains a summary of the picture and a few closing remarks.
II. Models of Distorted Sheets

A. Presentation of the Models

The hypothesis of the present paper is that projection effects in thin sheets can account for morphological, spectral, and kinematic observations of middle aged SNRs (in particular the Cygnus Loop). To test this hypothesis, the radial velocity and surface brightness structure were calculated for emission from material lying along a deformed thin sheet and having a velocity perpendicular to the sheet at every point. The calculations were performed in a plane defined by the line of sight and a line on the sky (analogous to a spectrograph slit). The sheet was assumed to be perpendicular to this plane. The results of such calculations for a few sheet geometries are shown in Figure 1. The output of each model includes a plot of the sheet geometry, the total surface brightness profile along the "slit" (summed over velocity bins), a 2-D "spectrogram" giving velocity structure as a function of position along the slit, and an extracted 1-D "spectrum." The sheet is initially assumed to be negligibly thin, and a width is put in after the fact by convolution with a Gaussian in the slit dimension. Ion temperature in the sheet, species mass, and an instrumental velocity resolution are input parameters and are used to determine the smoothing in the velocity
dimension. The models shown are all hydrogen with $T = 10,000$ K, $v_s = 100$ km s$^{-1}$, instrumental FWHM = 10 km s$^{-1}$, and a sheet width of 20 bins.

If the width of the sheet (20 bins = 10% of the slit length) is scaled to 1 arcsecond (or $\sim 10^{16}$ cm at the distance to the Cygnus Loop) then the results should be further smoothed by 60 or 80 bins FWHM before comparing with published spectra. In order to compare the kinematic results of the model calculations with the observations, 1-D "spectra" were extracted from the 2-D rasters by summing up a number of rows. The widths of these extractions varied from 2" to 9", using 20 bins = 1". (These spatial resolutions are typically better than those shown in SPGD for various echelle slit positions in the Cygnus Loop. They averaged at least three 2" scan lines to generate each of their 1-D line profiles.)

The synthetic 1-D spectra were then "reduced" following the methods of SPGD by fitting multiple Gaussians to the profiles. Since the temperature of the gas and the instrumental resolution are input parameters, the "turbulent" half-width $u$ (km s$^{-1}$ HWHM) due to bulk motion of the gas is just

$$u = \frac{1}{2} \left( v_{FWHM}^2 - v_T^2 - v_1^2 \right)^{1/2} = \frac{1}{2} \left( v_{FWHM}^2 - 23.6^2 \right)^{1/2} \text{ km s}^{-1}$$

where $v_{FWHM}$ is the measured full width at half maximum of a velocity component and 23.6 km s$^{-1}$ is the combined thermal
and instrumental full width. The parameter $u$ then characterizes the fit.

B. Discussion of Model Results

The set of models in Figures 1 a-f fall far short of covering the range of all plausible sheet geometries. Nonetheless, they do provide an idea of the aspects of the sheet geometry which affect the observed velocity and surface brightness structure. Conversely, they suggest how observed velocity profiles could be helpful in inductively reconstructing the three dimensional structure of observed filaments. The models A - F are arranged in what might roughly be considered an order of increasingly severe geometries.

In model A, a low amplitude sine wave is superposed onto a sheet with an average angle of $18^\circ$ to the line of sight. Even though the sheet never passes into exact tangency with the line of sight, these ripples give rise to filaments (appearing as parallel striations on the sky) with a surface brightness of 4.2 FOS (FOS $\equiv$ the brightness of a face-on shock) and a factor of 2 contrast between the filaments and the diffuse emission between them. The velocity profile of a filament and the surrounding diffuse emission is well approximated by a Gaussian with $u = 7.8$ km s$^{-1}$ HWHM, centered at 30 km s$^{-1}$. 
Model B shows a slightly larger amplitude disturbance in which a segment of the sheet is very nearly parallel to the line of sight. Geometries in which near tangency is maintained for a significant depth result in narrow, bright filaments (17.5 FOS in model B) with high contrast with the surrounding diffuse emission. The case where exact tangency is maintained is a critical case, and gives rise to filaments which are not much broader than the intrinsic thickness of the sheet. For geometries which only approach tangency (e.g., model A) or double back to give multiple tangencies (e.g., models C and D or the rippled sheets in models F-H) the apparent widths of the resulting "filaments" can be several times the sheet thickness.

The velocity component associated with the tangential portion of the shock is centered near \( v_r = 0 \, \text{km s}^{-1} \), and is fairly narrow (\( u = 5.6 \, \text{km s}^{-1} \) for model B). So long as the overall geometry does not actually turn back on itself, diffuse emission is seen on both sides of the filament. The projected velocities of both of the wings are in the same sense (toward the observer in this case), so sampling of the more face-on parts of the sheet gives rise to a wing on the negative side of the zero velocity peak. For model B, the profile is well fit by the central component and a broader component (\( u = 14.6 \, \text{km s}^{-1} \)) centered at \(-24.9 \, \text{km s}^{-1}\). This second peak contains about half of the total flux.
The characteristics of the wing in the velocity profiles for geometries similar to that in model B depends on the spatial rate at which the angle of the sheet to the line of sight is changing. A more abrupt departure from tangency gives rise to a broader wing (e.g., \( u = 19.6 \text{ km s}^{-1} \) for model D). In addition, for models B, C, and D the geometry of the sheet is symmetric about the center of the slit, so each end contributes to the wing in the velocity profile in the same way. If the two ends were very different from each other (say for example that one or the other broke very sharply) it would further broaden the wing, or perhaps cause the wing itself to separate into two components.

Model E is a simple geometry in which the sheet is curved outward. The surface brightness profile shows the sharp limb brightening seen in thin shells. The filament bounds a region of diffuse emission. Features displaying this characteristic are common in the Cygnus Loop. (See especially Figure 2c.) If the extracted 1-D spectrum in model E had sampled only the diffuse component of the emission, the velocity profile would have split up into two components. The profile shown is rather poorly fit by a single Gaussian, although the difference between the fit and the data would be hidden by a small amount of noise. The best fit to the profile is quite broad, having \( u = 19.4 \text{ km s}^{-1} \).
Models F - H introduce small scale ripples onto geometries similar to those in the previous models. (The fact that actual filaments show "condensations" or "knots" -- i.e., small scale variations in intensity -- along their lengths probably requires the presence of such ripples.) As noted above, these ripples cause the surface brightness feature associated with the near tangency of the sheet as a whole to be significantly broader than a sheet width. In addition, these ripples cause the velocity profile of a filament to be quite broad and asymmetric. In models B and D the strongest velocity component (associated with the part of the sheet which is tangent to the line of sight) was fairly narrow, while the wings were broad. (A knowledge of the absolute velocity of a component relative to the velocity of the system could help distinguish between these cases.) Ripples on the sheet, on the other hand, cause the strongest profile (associated with a portion of the sheet which is on average tangent to the line of sight) to be very broad. When fit with two profiles, models F - H have main components with \( u \) between 18.0 and 21.1 km s\(^{-1}\). Had the velocity profile in model F been fit with a single Gaussian (as such a profile may be when working with real data) it would have had a turbulent half-width approaching 30 km s\(^{-1}\).
C. Required Small Scale Structure

For a real interstellar shock to be as bumpy as the sheet geometries assumed in the models requires the preshock medium to be inhomogeneous at some scale. Assuming constant pressure and small disturbances, and inhomogeneity with wavelength \( x \) and amplitude \( \Delta \rho/\rho \) leads to a bump in the sheet with amplitude

\[
\Delta x = \frac{1}{2} \frac{\Delta \rho}{\rho} x.
\]

For rippled sheets as in models F - H, the required density inhomogeneities can be estimated by setting \( \Delta x \) equal to twice the amplitude of the sinusoidal ripple and \( x \) equal to its wavelength. For the model geometries, \( \Delta x = 5 \times 10^{15} \) cm and \( x = .6 - 1 \times 10^{17} \) cm, which requires density variations with an amplitude of 10 - 17\% of \( \rho \) and a scale length of \( \sim 10^{17} \) cm. These density perturbations are very mild in comparison with the variations (factors of 3 to 10 and scales \( \ll 10^{16} \) cm) required by various formulations of the small cloudlet picture (e.g., SPGD: Fesen, Blair, and Kirshner 1982).
III. Application to Observations of the Cygnus Loop

A. Spectral Properties and Brightness of Filaments

i) The Nature of Emission

Optical filaments in the Cygnus Loop have substantial line-of-sight depths. Parker (1967) and Miller (1974) inferred depths for the filaments they observed [e.g., $4\pi J_\nu / (n_p n_e^\text{eff} \lambda^4)$ for Balmer line emission] which were several times greater than their apparent widths of a few seconds of arc. Hester, Parker, and Dufour (1983, hereafter referred to as HPD) pointed out that the brightest filaments are often as much as 20 to 60 times the calculated face-on surface brightness of a radiative shock with parameters appropriate to the Cygnus Loop (e.g., Raymond 1979). HPD further noted that filaments were often spectrally indistinguishable from the surrounding diffuse emission. Hester (1985a) found the same to hold for the [O III] temperature inferred from $I(\lambda\lambda 4959, 5007)/I(\lambda 4363)$.

The application of the sheet model to these observations is straightforward. Filaments are seen at locations where a portion of the shock front is tangential to the line of sight. So long as the physical parameters of the shock do not change much along the line-of-sight depth of the filament, and ignoring such complications as
foreground or background emission, the filament should be spectrally similar to the surrounding diffuse emission. On.

Clouds in the preshock medium must be at least as large as observed filaments, and can be much larger (see Section III.C). Filaments showing essentially steady flow emission similarly require clouds with substantial column depths ($N_H \approx 5 \times 10^{17} \text{ cm}^{-2}$ for a 100 km s$^{-1}$ shock and a preshock density of 10 cm$^{-3}$ -- e.g., Shull and McKee 1979).

ii) Reasonable Geometries

Filaments in the Cygnus Loop often bend, appear, and fade out on scales of $\lesssim 1'$, and show geometries at least as complex as those assumed by the models to exist along the line of sight. The suggested scale for the model geometries corresponds to a slit length of 10" and a depth for the geometry of 30" $\approx 3 \times 10^{17}$ cm. At this scale the geometries assumed to be present along the line of sight are much like the geometries observed to be present in the plane of the sky (i.e., the geometries of observed filaments), and so should give results which apply to the Cygnus Loop.

Table 1 lists the peak brightness of the filaments formed by the geometries in Figure 1 in units of FOS ($= \text{brightness of a face-on shock}$). They have an average depth of 13 FOS. Also listed are the H$\alpha$ surface brightnesses of a number of features along the spatial profiles presented by
HPD. When normalized to the surface brightness of Raymond's model D ($n_0 = 10 \text{ cm}^{-3}$ and $v_\text{s} = 81.5 \text{ km s}^{-1}$) they have an average of 13 FOS as well. The similarity of these values provides an important check for both the assumed geometries and the sheet model as a whole. The predicted face-on surface brightness of shocks, combined with sheet geometries suggested by the observed geometries of filaments, lead to the observed brightness of the filaments.

8. Filamentary Morphology

Figure 2 shows [O III] $\lambda5007$ images of three regions around the Cygnus Loop. Figure 3 is a print of a red Palomar Schmidt plate of the entire Loop taken by R. A. R. Parker. The morphology of the emission is hard to characterize in words. The emission consists of numerous filaments, with sizes ranging from $\lessapprox 1'$ to many minutes of arc, embedded in more diffuse but still irregular emission. Filaments lie at all angles, but are preferentially aligned with the edge of the shell. Sets of parallel filaments and filaments which branch and fork are common. Figures 2b and 2c in particular show a number of clear examples of filaments bounding regions of diffuse emission.

A ripple in a sheet appears as a filament with surrounding diffuse emission. Limb brightening in a thin sheet that doubles back at tangency gives a filament which
bounds diffuse emission. A question that remains, however, is whether a large sheet with bumps and wrinkles caused by slight inhomogeneities in the cloud will necessarily produce the observed overall morphology of the regions of optical emission.

i) An Analog Representation of the Shock Front

Figure 4 shows images of the shadow cast by a thin bumpy sheet of "optically thin" material (i.e., common window screen). The darkness of the shadows increases with the line-of-sight depth through the distorted sheet. Hence these are a very good analog representation of an optically thin radiative shock front. (The analogy is simpler than reality, where conditions may change along the face of the shock front. The screen is also more constrained than an actual shock in the geometries it can assumed. The screen can only be distorted into shapes which approximately conserve its surface area both locally and globally.)

It is important to note that the bumpiness of the sheet is more or less uniform across its face. Regions of filaments are observed not where bumpiness happens to occur, but rather where the large scale distortions of the sheet bring portions of it near tangency. In nature the general shape of the sheet is due to the shell geometry and the overall shape and density structure of the cloud. The small
scale bumpiness which gives rise to filaments is due to smaller scale inhomogeneities such as those discussed in Section II.

ii) Comparison with the Observed Morphology

The similarities in the appearance of the shadows with the actual remnant are remarkable. Note initially that the average alignment of filaments is determined by the orientation of the average surface of the sheet to the line of sight. Hence, collapse perpendicular to field lines or other mechanisms need not be invoked to explain the observed alignment.

Near tangency of a small portion of the sheet to the line of sight is required to get a single filament. So long as the average face of the sheet is close to tangency with the line of sight, the degree to which the sheet must be perturbed to give rise to filaments in projection is small. Thus, regions containing many filaments are more likely to be seen near the projected edge of the shell where the shell geometry of the remnant guarantees that the sheet will be close to tangency. Filaments are still allowed well away from the edge, however, so long as the sheet is sufficiently deformed.

In Figure 4a the screen actually turns back on itself. This gives rise to very bright filaments (or at least a
contiguous line of filaments) along the edge of the region, as well as a somewhat strong diffuse component between filaments. If the sheet folds back sharply enough, the filaments at the edge can be fairly faint. Interestingly, few of the regions of bright emission around the rim of the Loop clearly exhibit this type of behavior. The NE (Figure 2a) doesn't show such a hard edge at all, even upon examination in the deep Palomar image (Figure 3). The W (Figure 2b) shows an edge more like that in Figure 4a, as does the northern portion of the SE (Figure 4c). The existence of faint filaments and diffuse emission outside these edges shows that the local tangency of the sheet to the line of sight is not the outermost projected edge of the shell, however. The only filaments whose morphology really satisfies the requirements imposed by the assumption that they lie at the real projected edge of the shell are the faint Balmer line filaments (e.g., Gull et al. 1977) which are coincident with the edge of the X-ray shell (Raymond et al. 1981; Ku et al. 1984). These comparisons confirm the suggestion (Hester and Cox 1985) that the appearance of optical emission interior to the edge of the X-ray shell does not require that the optically emitting regions have been engulfed by the blast wave.

The overall morphology of both the NE and the W are better matched by Figures 4b which show large scale "waves" on the face of the sheet which bring portions of it into
near tangency interior to the projected outer edge of the shell. Note in particular the similarity between the right hand side of Figure 4b (the two complexes of emission joining in a V) and the southern part of the emission on the west side of the Loop (Figure 3). Figure 4b also shows quite well how diffuse emission arises from the geometry. The details of how the edge of the sheet fades out need not be of concern. Unlike a face-on screen, a face-on shock is essentially invisible. Extending the geometry shown in the left hand side of Figure 4b over long distances would give rise to extended lines of filaments such as those seen running N-S across the face of the Loop to the west of center.

Figure 4c shows a more extremely warped sheet. Comparison with the SE (Figure 2c) shows many similarities. The change in the average direction of the filaments seen in the northeastern part of Figure 2c is similar to that in the right hand side of Figure 4c. The "V's" in the western and southeastern part of Figure 2c (HPD's Region III and the vicinity of XA in Hester and Cox) are similar to a feature in the left side of Figure 4c, which arose from a fairly sharp indentation into the sheet.

Figure 4d shows cases where on average the sheet is not far from tangency (within ~ 20°) over an extended region. This shows the small scale structure of the filamentary emission fairly well. Essentially the entire range of small
scale behavior of the observed filamentary appearance of the Cygnus Loop and other SNRs (e.g., parallel striations, filaments that branch and rejoin, various widths of filaments, etc.) can be observed in this figure. In addition, the overall morphology in Figure 4d is very similar to that of the "carrot" (NGC 6974) in the northwest part of the Cygnus Loop. (Excellent images of the carrot, as well as other parts of the Loop, can be found in Fesen, Blair, and Kirshner 1982, Figure 6.) The applicability of a sheet geometry is particularly easy to see for this field, which is considerably more face-on that the emission of the E and W limbs. The eastern edge of the carrot is generally brighter than the western portion, especially in [O III], and has a fairly "hard" edge. This suggests that the average surface of the sheet turns more tangential to the line of sight there. The east edge of the carrot can be followed down the face of the Loop in the series of long N-S filaments mentioned above. This could be due to emission from a sheet wrapping around the edge of a single large cloud, which runs the length of the Loop and is most dense at its northern end. The 21-cm maps of DeNoyer (1975) in fact show both ~ N-S HI contours through this part of the Loop and strong emission from the vicinity of the carrot.
iii) Morphological Differences Between Emission Lines

While most filaments in the Cygnus Loop are seen in a range of emission lines (HPD), the detailed characteristics of the filaments (location of knots, width of the filament, etc.) may vary. This is due to the fact that the [O III] emitting sheet and the Hα and [N II] emitting sheet (i.e., the recombination zone), for example, are different sheets (although their separation is generally smaller than the resolution of ground based imagery).

Several factors play a role in the differences between the [O III] and Hα sheets. The [O III] sheet is closest to the shock front itself, has a fairly small column depth, and is almost always thin. The Hα sheet, on the other hand, is further from the shock, has a larger column density (and hence a greater memory of inhomogeneities in the preshock ISM), and may be quite thick if magnetic fields limit the compression in the recombination zone. It is also this zone which is most subject to thermal instabilities and so might be expected to be less smooth.\(^{(1)}\)

\(^{(1)}\)Thermal instabilities almost certainly affect radiative shocks, but to date their understanding is limited. Calculations by McCray, Stein, and Schwarz (1972) have suggested that, since conduction is inhibited across magnetic fields, thermally unstable collapse may occur
Morphological differences could also have to do with scales for inhomogeneity in the preshock medium. If the scale length for inhomogeneities decreases as the density of the cloud increases, slower shocks which are stronger in Hα relative to [O III] would be rippled on smaller scales than faster shocks, and hence in projection would give rise to shorter, less regular filaments.

perpendicular to field lines. Sources of "anomalous conduction" such as MHD waves (e.g., Hartquist and Morfill 1984) may damp this instability. Smith and Dickel (1983) show that ropes formed by this instability are flattened by the dynamics of the shock. The author wonders if the dynamics of the shock might inhibit the onset of the "rope-building" instability. Chevalier and Imamura (1982) and McCray, Stein, and Kafatos (1975) discuss instabilities which do not violate the plane-parallel assumption. These might be affected by radiative coupling by UV photons between the hot zone immediately following the shock and the photoionized recombination zone. Continued investigation of these processes is very important.
iv) A Few Objections

a) Curvature of Filaments

One objection to this picture, originally raised in print by McKee and Cowie (1975), is that shocks encountering spherical clouds should be convex inward, while many filaments at the edge of the Cygnus Loop are convex outward. This objection implicitly assumes that each filament corresponds to a single shocked cloud. In the case of a large sheet-like front moving into a single cloud, however, a filament which is convex inward in interior to the surrounding surface of the sheet, and additional filaments are likely to be seen further out than that point. A filament which is convex outward, on the other hand, is exterior to the surrounding surface of the sheet and may be seen at the local projected outer boundary of the emission. The tendency for filaments to be convex outward is most prominent in [O III], suggesting that this is a property primarily of faster portions of the front. This, too, is a natural consequence of the sheet geometry. Portions of a large shock front which are travelling faster than average must be convex outward if they are to proceed ahead and yet remain contiguous with the slower portions of the front.

The curvature argument could also be applied to the overall shape of complexes of emission. The overall shape
of a large complex of emission associated with a single cloud should perhaps be convex inward. Initially, the overall edge of the optical emission is convex inward at many points around the Loop. (See Hester and Cox 1985 for a discussion of indentions in the shell.) The argument that all complexes should be convex inward depends critically on assumptions about the shape of the cloud. When encountering a wall (such as on the W limb of the Loop) or a sheet-like cloud (e.g., McCray and Snow 1979 for review) the shell should be curved outward. Even assuming a spherical cloud, the projected leading edge of the emission will be determined by the intersection of the blast wave and the boundary of the cloud, and may be seen in projection to be convex outward.

b) Radio Brightness of Filaments

Straka et al. (1985) argue against a sheet geometry on the basis of the appearance of filaments in a high resolution 18 cm radio continuum map of the NE rim of the Cygnus Loop obtained with the VLA. They present two arguments: (1) there appears to be no anticorrelation between the radio brightness of filaments and their widths; and (2) the relativistic particle density of the sheets would have to be low. The first of these objections assumes that the total flux from each filament should be about
constant, and so wider filaments should be fainter. Variations in the intrinsic surface brightness of the sheet and the line-of-sight depths of filaments invalidate this assumption and dominate the characteristics of filaments.

Assuming that compression occurs perpendicular to field lines and that the relativistic electrons conserve their first adiabatic invariant, the emissivity $\varepsilon_v(n_2)$ in the compressed region is related to the ambient emissivity by

$$\varepsilon_v(n_2) = \left(\frac{n_2}{n_0}\right)^{2-2\alpha} \varepsilon_v(n_0)$$

where $\alpha$ is the spectral index of the emission and $\varepsilon_v$ is the emissivity of the ambient medium (e.g., Duin and van der Laan 1975; Dickel and Willis 1980). Assuming $\alpha = -0.5$ (DeNoyer 1974) gives $\varepsilon \propto (n_2/n_0)^3$. Scaling the average synchrotron emissivity of the ISM at 49 cm [$\varepsilon(49 \text{ cm}) \approx 3 \times 10^{-39} \text{ ergs s}^{-1} \text{ cm}^{-3} \text{ Hz}^{-1}$ -- Baldwin 1967] to 18 cm, assuming a power law distribution of electrons with $\gamma = 1.6$ (Fanselow et al. 1969), gives $\varepsilon(18 \text{ cm}) \approx 1.89 \times 10^{-40} \text{ ergs s}^{-1} \text{ cm}^{-3} \text{ Hz}^{-1} \text{ sr}^{-1}$. The emissivity of the bright filaments in the NE part of the Cygnus Loop calculated from the VLA observations (Straka et al.) is

$$\varepsilon_{\text{obs}}(18 \text{ cm}) = 7.35 \times 10^{-18} \frac{1}{l} \text{ ergs s}^{-1} \text{ cm}^{-3} \text{ Hz}^{-1} \text{ sr}^{-1}$$

where $l$ is the depth of the filament in cm. Assuming that $\varepsilon_v(n_0)$ is given by the average value yields
\[ \left( \frac{n_2}{n_0} \right)^3 \lambda = 3.88 \times 10^{22} \text{ cm}. \]

Assuming a compression ratio of 50 gives \( \lambda = 3.1 \times 10^{17} \) cm, in good agreement with depths inferred from the optical data.

The preceding discussion is not meant to be a rigorous determination of the depths of radio filaments. The value of \( \lambda \) is very sensitive to a number of assumptions and parameters which are not well known. This discussion does show, however, that reasonable assumptions can lead to estimated filament depths which are not unlike those obtained from the much better understood optical determinations.

C. Kinematic Data

The kinematic structure of the gas composing the filaments in the Cygnus Loop and several other SNRs have been studied using long-slit echelle spectroscopy by SPGD. They observed that velocity profiles of lines were often asymmetric and composed of several easily identifiable components. Figure 5 shows a sample of the observed line profiles taken from Shull (1982). As noted above, these profiles are spatially averaged over 6" or more.
By comparing the velocity dispersions of ions having significantly different masses, but which are expected to be found in the same part of the cooling regions behind shocks, SPGD were able to separate out the thermal and "turbulent" contributions to the velocity dispersions. For the Cygnus Loop, observations of Hα and [N II] typically yielded thermal widths characteristic of ~20,000 K and "turbulent" velocities \( u \) between 2 km s\(^{-1}\) and 29 km s\(^{-1}\) HWHM, with an average of 14.6 HWHM and an rms dispersion of \( \pm 5.4 \) km s\(^{-1}\) for 33 "knots." This turbulent motion was interpreted as being due to the chaotic motion of unresolved "cells" of gas within the emission volume.

The hypothesis of turbulence does not directly explain why line profiles are observed to break up into discrete components or the presence of significant asymmetries in the profiles of individual components. These phenomena seem to require some type of ordered motion. In addition, there was no other evidence suggesting the presence of the postulated turbulent elements.

Within the context of a sheet geometry, the observed kinematic structure would largely result from simple projection of a fraction of the sheet velocity along the line of sight. (Motions associated with thermal instabilities in the cooling and recombination region and the velocity gradient of \( \sim 0.25 v_s \) across the cooling and recombination zone could complicate this picture somewhat.)
The presence along a line of sight of discrete components having different average radial velocities would result from multiple crossings of the sheet. If each crossing is at a slightly different angle, then the components would correspond to the different projections of the velocity of the material behind the shock along the line of sight. The broadening of individual components could be due to variations in the projection angle of the sheet on scales smaller than the spatial resolution of the spectrograms. This possibility was quantified in Section II.B.

For individual filaments it should be possible to compare observed surface brightness profiles, velocity profiles, and shock parameters derived from spectrophotometry with model geometries to decide whether a sheet description is appropriate (and if so, determine a geometry). In practice, this will require coordinated observations chosen specific to the task. It is possible, however, to make some quantitative and qualitative statistical comparisons with published data. The same geometries which were shown in Section III to be consistent with the morphology of the Cygnus Loop and the brightnesses of its filaments must also account for the types and widths of velocity profiles of filaments found in general.

Table 2, taken from Table 3 of SPGD, presents measured turbulent widths for the Cygnus Loop. Also presented are the results of fitting the synthetic spectra of Section II.
While the total widths and the "instrumentally corrected" widths $v_H$ obtained from the models are smaller than observed (due to the cooler $T$ and better velocity resolution assumed in the models), the range of the "turbulent" widths $u$ and the "turbulence" $Q_H$ arising from fairly simple geometries can easily account for the observations.

SPGD briefly considered the possibility that projection effects might contribute to turbulent widths, but dismissed the idea. They noted that IC 443 has a lower average shock velocity than the Cygnus Loop (Fesen and Kirshner 1980) but a higher average turbulent velocity, and argued on this basis that $u$ and $v_s$ are not related. However, this comparison fails to account for the fact that the Cygnus Loop is better resolved than IC 443, which is about twice as far away (Fesen 1984). In a sheet geometry the observed "turbulent" width will increase as more of the sheet is averaged.

SPGD observed broad components associated with diffuse emission in many of the line profiles for the NE part of IC 443, and noted that the measured turbulent widths of these components bracket the average shock velocity of 70 km s$^{-1}$ determined spectrophotometrically by Fesen and Kirshner. This suggests that in IC 443 emission was arising from both the receding and approaching portions of the shell along the same line of sight. In the Cygnus Loop NE and SE, where the
emission appears to be on one side of the shell or the other, such broad wings are not common.

D. X-ray Emission

There is a large scale correlation between regions of bright X-ray emission and the optically bright portions of the Loop (Ku et al. 1984). In addition, the sharp edge of the brightest X-ray emission on the eastern limb of the Loop corresponds to within the resolution and alignment uncertainties of the data (~ 10") with the leading edge of the optical emission. Working within the context of the picture being discussed here, Hester and Cox (1985) found that the observations are directly accounted for by the combined effects of a denser than average preshock medium associated with the diffuse envelopes of large clouds and the "inertial pressurization" of already shocked material behind the blast wave. The blast wave slows as it encounters the cloud. This forces the material behind it to rapidly decelerate, converting its momentum into pressure and enhancing its X-ray emissivity.

E. Spectral Structure

In the Cygnus Loop, relatively faint X-ray emission forms a complete shell (e.g., Ku et al. 1984). The
characteristics of the optical emission vary in a fairly systematic way with increasing distance behind the projected edge of that shell (Parker 1973). At the edge of the X-ray shell, faint optical filaments are sometimes observed, generally in association with bright X-ray emission and not far removed from regions of bright optical emission. These filaments are visible primarily in Balmer line emission from hydrogen. Chevalier and Raymond (1978) interpreted this emission as being due to collisional excitation of neutral hydrogen prior to its complete ionization by a relatively fast shock ($v_s = 130 \text{ km s}^{-1}$ -- Raymond et al. 1981, 1983) being driven into a partially neutral medium with a density ($\sim 2 \text{ cm}^{-3}$) intermediate between the clouds and the average intercloud phase.

The edge of the bright optical emission is typically found several minutes of arc behind the edge of the faint X-ray emission. Moving inward toward the center of the Loop, the first optical emission to be found is "type II" -- HPD's notation for features which are seen only in emission from [O III] and other "hot" species. Over the next 20" or so, features are seen to appear in the light of emission from species found in progressively more of the cooling and recombination regions (Fesen, Blair, and Kirshner 1982; HPD), until the onset of "type I" features, which are seen in lines ranging from [O III] through [O I]. The type I
emission further shows a gradient in velocity sensitive line ratios such as [O III]/Hβ (HPD).

The interaction of the blast wave with an idealized large spherical cloud is shown in Figure 6. The perspective in Figure 6 is looking along the plane of the unperturbed blast wave. The cloud is assumed to be denser toward the center and be surrounded by an intermediate density envelope. [Note that the boundary between the "cloud" and the "envelope" need not be a discontinuity. Rather, the cloud boundary may be thought of as being defined by the density at which shocks become radiative on the appropriate time scales at the applicable pressure (Hester and Cox 1985).]

The envelope around the cloud provides the medium necessary for the formation of the faint Balmer line filaments, as well as the denser preshock medium implied by the bright X-rays. The location in projection of the bright optical emission behind the X-ray edge is partly due to the fact that the cloud forms an indentation into the shell, and partly due to the failure of the cloud to intersect the shell exactly at the projected edge.)

With distance inward from the ring-like locus of the intersection of the the blast wave and the cloud the amount of time since a cooling region began forming increases, and hence the region becomes increasingly more complete. This is the transition from type II through type I.5 to type I
emission. As the shock moves deeper into the cloud the preshock density increases, and the shock slows. Thus throughout the transition from type II emission to type I emission and continuing across the part of the shock which is essentially steady flow there is a steady decrease in inferred shock velocity with increasing distance toward the center of the cloud.

Figure 7 shows three different perspectives on the blast wave/cloud encounter of Figure 6, with particular emphasis on the variations in completeness of the cooling and recombination behind optical shocks. Figure 7a is from the same perspective as Figure 6, but shows more explicitly the bands where different feature types are found. As in HPD, the radial scale for the transition from type II to type I is given by the difference between the velocity of the blast wave and the velocity of the radiative shock times the time scale for establishing steady flow. The fact that the progression through feature types is radial (i.e., along a line pointing to the center of the remnant) is due to the perspective adopted and the spherical geometry assumed for the cloud. A similar structure could evolve without the assumption of a spherical cloud as portions of the shock encountering denser material slow and lag behind faster portions. (This is also probably necessary to explain the general decline in $v_s$ with distance behind the leading edge after the onset of completeness.)
Figure 7b shows the encounter from a face-on perspective. The zone of type II emission surrounds the type I emission. In this case, the average surface of the shock is nowhere approaching tangency to the line of sight, so filaments should be somewhat diffuse and faint. The portion of the shock closest to tangency is the nonsteady flow portion, so "isolated" groups of type I.5 and type II filaments might arise in this perspective.

An oblique view of the cloud is presented in Figure 7c. The "radial" transition from type II to type I seen in Figure 7a is preserved from this perspective. The average face of the shock along the "leading edge" nonsteady flow zone is now further from tangency with the line of sight, however, so leading edge type I.5 and type II filaments should be less pronounced. An exception to this is the tip of the cloud (which is emphasized in the figure) where the sheet must pass through tangency at some point as it crosses over to the back side of the cloud. From this perspective, then, the brightest type I.5 and type II emission might appear as a wing on the side of a region of predominately type I emission. This perspective also allows for nonsteady flow emission on the far side of the cloud to appear in projection to be imbedded in or even trail the zone of type I emission.
IV. Summary and Concluding Remarks

The present paper discusses the hypothesis that sheet-like shock fronts propagating into large clouds can complete a picture accounting simultaneously for essentially all of the observational data for the Cygnus Loop SNR. These data include: (1) spectral properties and surface brightnesses of filaments, (2) the observed filamentary morphology of the emission, (3) the velocity profiles of filaments, (4) the characteristics of filaments at radio wavelengths, (5) the X-ray morphology of the Loop, and (6) the changes in the character of emission with increasing distance behind the projected edge of the shell.

Filaments are interpreted as line of sight projections of portions of the sheet. Variations in the projection of the shock velocity along the line of sight, calculated assuming sheet geometries which are consistent with both the morphology of filaments and their surface brightnesses, lead naturally to "turbulent" velocities consistent with observation. Characteristics of velocity profiles which might be helpful in trying to reconstruct the 3-D geometry of filaments are discussed.

An analog model of a large, distorted, bumpy shock front is presented and shown to produce the observed morphology of the remnant's prominent optical filaments. Comparisons with the observed morphology supports the idea
of Poveda and Woltjer (1968) that regions of optical emission lie on the local outer boundary of the shell, and have not been engulfed by the blast wave. Differences in the appearance of the Loop in emission from different species result mainly from transitions from young nonsteady flow shocks to older shocks in which complete cooling and recombination regions have had time to form. Thermal instabilities may be responsible for differences in individual filaments.

Bright X-ray emission arises from an intermediate density preshock medium. Exceptionally bright X-ray emission associated with optical emission is the result of inertial compression or reshocking of hot material behind the rapidly decelerating blast wave encountering a denser medium. Radio filaments, which largely coincide with optical filaments, are due to synchrotron emission from the recombination region where the magnetic field is strong. The surface brightness of radio filaments are consistent with the van der Laan mechanism applied in a sheet geometry.

Detailed comparisons between individual filaments and specific sheet geometries could be made if both morphological and spectral information were available. For particularly simple geometries it may be possible to interpret the surface brightness profile of a filament directly as the spatial gradient of the sheet geometry, but comparison between a geometry inferred in this way and
velocity data might be complicated by unresolved ripples on the sheet. The characteristics of velocity profiles discussed in Section II.B would help resolve such an ambiguity.

The fact that structure which can influence velocity profiles remains unresolved in ground-based observations suggests that the Hubble Space Telescope may be indispensable for complete (and unique) reconstructions of filamentary geometries. This observatory will also yield remarkable observations of the structure of the emission and flow behind radiative shocks. At .1" resolution, a cooling region behind a radiative shock in the Cygnus Loop will become a well resolved source, showing the distribution of emission from various ions (e.g., [O III], [O II], Hα + [N II], and [O I]). The detail gained from these observations will undoubtedly help resolve a number of outstanding issues (e.g., the affect of instabilities on the flow) and improve our understanding of the physics of these systems. This will also improve the confidence with which emission from shock waves may be used as a diagnostic tool.
TABLE 4.1
Peak Surface Brightnesses of Observed Filaments
and Model Profiles

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<th>HPD Features</th>
<th>Designation</th>
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<th>$I(\text{FOS}^{(2)})$</th>
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\[<I/\text{I}(81.5)> = 13.2 \pm 9.2^{(3)}\]

\[<I(\text{FOS})> = 13.1 \pm 4.0^{(3)}\]

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\(^{(1)}\) Calculated Surface Brightness of Raymond's (1979) model D with $v_s = 81.5 \text{ km s}^{-1}$ and $n_0 = 10 \text{ cm}^{-3}$.

\(^{(2)}\) FOS $\equiv$ Surface brightness of a face-on shock.

\(^{(3)}\) Sample rms deviation.
### TABLE 4.2

Comparison of Observed and Modeled "Turbulent" Velocities

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\[
\langle u \rangle = 13.6 \pm 6.0 \text{ km s}^{-1} \text{ HWHM}
\]

\[
\langle u \rangle = 14.6 \pm 5.4 \text{ km s}^{-1} \text{ HWHM}
\]

(1) From Shull et al. (1982).

(2) $v_{\text{FWHM}}$ = Raw measured FWHM of component.

(3) $v_{\text{H}}$ = HWHM, instrumental broadening removed.

(4) $u$ = HWHM "turbulent" velocity.

(5) T determined from comparison of He and [N II].

(6) $Q_{H} = u/v_{H}$ = "turbulence" (Shull et al. 1982).

(7) Sample rms deviation of measurements.
FIGURE CAPTIONS

Figure 4.1. Surface brightness and velocity profiles calculated from sheet geometries. The vertical box on the right side of each figure shows a sheet geometry. The horizontal axis of the box is a line along the plane of the sky, and the vertical dimension is the line of sight. The sheet is assumed to be perpendicular to the plane of the paper, and is moving from left to right, with a velocity perpendicular to the sheet at all points. The horizontal tick mark shows the intrinsic width of the sheet, assumed to be 1" (~$10^{16}$ cm for the Cygnus Loop).

The small box in the top right hand side of each figure shows the surface brightness profile across the "filaments" resulting from the assumed geometry. The peak brightness is labeled in units of FOS (= the brightness of a face-on sheet). The dotted lines show the approximate surface brightness of the filament for portions of the slit where the sheet ran out of the ends of the box used for the calculation.

The box in the upper left part of each figure shows a synthetic "spectrogram" generated from the assumed geometry. The vertical axis is the plane of the sky, with the top of the axis corresponding to the left side of the slit in the plot of the sheet geometry. The vertical tick shows the intrinsic sheet width. The horizontal axis is the radial
velocity, computed from the projection of the sheet velocity along the line of sight. The horizontal tick, labelled 23.6 km s\(^{-1}\), gives the combination of the assumed thermal and instrumental velocity widths.

The plots at the bottom of each figure show extracted 1-D velocity profiles. The extractions were made by summing a number of rows from the synthetic spectrogram. The widths of the extractions varied from 35 rows to 185 rows (\(\sim 2''\) to \(9''\)). Each profile is labeled with the row numbers used (which start at 0 on the top of the spectrogram and run to 199 at the bottom). The resulting profiles (X’s) were fit by the sum of one or more Gaussian profiles (solid lines = sum; dotted lines = individual profiles) plus a linear continuum (dashed lines). The characteristics of the fit are given below the profile.

Figure 4.2. Images of portions of the Cygnus Loop, taken in the light of emission from [O III] \(\lambda 5007\). Figure 2a is a mosaic of six frames obtained with the CCD camera on the No. 1 0.9-m telescope at Kitt Peak National Observatory. It shows the NE rim of the Loop. Figures 2b and 2c were obtained with the CITD camera on the No. 1 0.9-m at KPNO. They show portions of the W and SE limbs, respectively. Stars have been suppressed in Figures 2a and 2c.
Figure 4.3. A red light image of the Cygnus Loop taken with the Palomar Schmidt telescope by R. A. R. Parker.

Figure 4.4. Shadows of a deformed and bumpy sheet, showing the filamentary morphology which naturally arises when this geometry is viewed in projection.

Figure 4.5. Velocity profiles of emission from the Cygnus Loop (from Shull 1982).

Figure 4.6. The interaction of a blast wave with a large, idealized spherical cloud. The perspective is looking along the plane of the undistorted blast wave.

Figure 4.7. Three perspectives on the blast wave / cloud encounter shown in Figure 6, by primarily emphasizing the structure of the optical emission. Figure 7a is a view looking down the undistorted blast wave (as in Figure 6). Figure 7b is a face-on view. Figure 7c is an oblique view, with emphasis on the tip of the region of emission.
Figure 4.1a
Figure 4.1b
Figure 4.1d
Figure 4.1e
Figure 4.1f
Figure 4.1g
Figure 4.1h

Sample rms error: 4.23529
Background: 0.72321 ± 0.00815706λ + 0.0001λ(λ+2)
LINE 1: Height: 227.93 Center: -7.73
FWHM: 29.19 Area: 7083.2
LINE 2: Height: 545.48 Center: 36.74
FWHM: 48.42 Area: 28115
Figure 4.4a
Figure 4.6
Figure 4.7a
Figure 4.7b
Figure 4.7c
CHAPTER 5

CCD IMAGERY OF THE NE LIMB

I. Introduction

The preceding chapters of this thesis have presented the results of research which is essentially complete. This research has established a framework for understanding a wide range of optical, X-ray, radio, and UV observations of the Cygnus Loop. Despite the extent of the work presented, however, only a small fraction of the Cygnus Loop has been studied in detail. Continued investigations are necessary in order to test and refine our basic picture of the Cygnus Loop, explore the range of conditions present, and especially to see what surprises this remarkable object has left in store.

In previous discussions, the quantitative optical imagery data have largely been limited to those of the SE presented by HPD. These were photographic image tube plates, and the field analyzed was only ~ 5’ X 10’ in size. The present chapter presents the results of new calibrated digital imagery of the bright NE limb of the Loop in emission from Hα, [O I], [O II], and [O III]. This data is
similar in kind to that presented and discussed by HPD, but of higher photometric accuracy. It will be discussed only briefly and in a comparative manner. This data was obtained originally to provide a base for comparison with a high resolution radio continuum map obtained with the VLA by Straka et al. (1985) and X-ray images obtained with the Einstein Observatory by Ku et al. (1984). (It was hoped that the X-ray and radio data could also be included in the present work, but these data did not become available in a timely manner.) The optical data will also be used to provide quantitative surface brightness profiles for comparison with velocity measurements which Raymond and Hester hope to obtain later in 1985.

Apart from the fact that optical data of a second region of the Loop are interesting in their own right, they are included here largely because they represent a week's worth of hard-won telescope time and perhaps six man-months of reductions and software development. Moreover, presentation of these new CCD data, based on more modern "state of the art" techniques than those of HPD, are useful for assessing the scientific benefits of such improved imagery.
II. Observations and Data Reduction

Six overlapping fields along the NE rim of the Cygnus Loop were imaged using the RCCD direct camera at f/7.5 on the No. 1 0.9-m telescope at Kitt Peak National Observatory. The observations were made over the course of five partly cloudy nights in August 1983. The RCCD direct system employs a 512 row by 320 column RCA charge coupled device (CCD) detector onto which the telescope images directly. Thirty-two columns of the detector are masked and used to obtain a bias level for each frame, so the array used for data is 512 X 320. The pixel size is 30 μm = .86 arcseconds at f/7.5, giving a field size of 7' 20" E-W by 4' 35" N-S for each individual CCD frame. Table 1 lists the approximate coordinates of the center of each field. Figure 1 shows the relative placement of each field. (These subfield numbers are used in the discussion of Section III to describe locations of features.) Each field was imaged through filters which isolate Hα λ6563, [O I] λ6300, [O II] λ3727, [O III] λ5007, and a continuum bandpass used to map star positions. Table 2 lists the exposure data.

All frames were bias corrected, trimmed of the overscan region, and divided by dome flats, which were taken at the beginning and end of each night. This preliminary processing was done after each night's observing using the standard KPNO CCD Mountain Reduction routines. Division by
dome flats adequately removed fringes in the images which arise in narrow-band imagery due to interference in the thin coating of the detector. All additional reductions were carried out using the image processing facilities at Rice University.

Bad pixels resulting from cosmic ray events, poor data around the edges of the field, and a bad column on the chip were flagged as "blanks." Next, the data were filtered to flag pixels which were more than $2\sigma$ from the mean of the surrounding 3 X 3 pixel window. All "blank" pixels were then replaced with the average of the surrounding 5 X 5 pixel box. The full width at half maximum (FWHM) of a number of star images in each frame were measured before filtering. After filtering, each frame was smoothed by convolution with a Gaussian with a width such that the smoothed frame had a FWHM "seeing" of four pixels = 3.5". This procedure compromises the resolution of the data somewhat, but assures that later comparisons between rasters are not affected by differences in resolution and provides adequate signal to noise in the weak [O I] rasters.

Positions of ~25 stars were measured to an accuracy of ~.1 pixel in each of the frames. The positional measurement used an algorithm which demands that the centroid of the data enclosed by a circular aperture with a size comparable to the star image lie at the center of the circle. Positions of stars which lay in regions of overlap
between adjacent frames were measured in the continuum frames, and used to determine X and Y offsets between each frame. The complete set of star positions measured in the continuum frames then defined a standard coordinate system for the region as a whole, onto which each of the line rasters could be mapped.

Adjacent rasters taken in the light of the same line were normalized to each other using the results of a linear least squares fit to data values in the region of overlap between the fields. This corrected for both offsets and differences in scale between the frames. This normalization procedure worked very well for the [O III] and H-alpha images. Treatment of the [O II] data was complicated by the inability of the filter bolt on the RCCD mount to accommodate both the [O II] interference filter and its blocking filter. The unblocked [O II] filter had a leak of several percent at wavelengths longward of about 7000 Å.

Fortunately, the emission lines between 7000Å and 1.5 μm are weak in comparison to [O II] λλ3727 in the spectrum of radiative shocks (e.g., Raymond 1979), so the contamination of the image by long wavelength line emission is slight and the images still accurately represent the [O II] surface brightness. The red leak did allow contamination by continuum emission from red stars, and also made it impossible to reliably flat field the [O II] data. The [O II] frames showed slight gradations in background and
sensitivity as a result. These were not accurately
corrected for, and remain as an overall variation in the
background of the final [O II] raster.

An uneven background with a consistent spatial
distribution but varying overall strength was present in the
[O I] frames following the initial reductions. This
background was not fringed like the line data, and decreased
in strength away from a peak at the middle of the north side
of the frame. The background was apparently due to a light
leak in the system, and was presumably not apparent in the
other lines either because of their greater surface
brightness than [O I] (and the resulting shorter exposures),
or because the light leak was associated with the position
of the filter bolt. The shape of the background was
determined using an [O I] sky flat, was normalized to each
[O I] frame in regions apparently free of nebular emission,
and was then subtracted from the frame. The [O I] frames
were then normalized to each other as described above.

All frames in a given line were aligned with the
"standard" coordinate system defined by the continuum frames
and placed onto monochromatic mosaic rasters. Alignment to
better than a pixel was achieved by extrapolating between
values of the four pixels surrounding the computed position
of an "output" pixel in the "input" raster. Of course, this
procedure slightly affects the point spread function of the
images. Data were averaged in regions where two or more
individual frames overlapped. The mosaic generated from the continuum frames was used to produce a mask for pixels contaminated by star light. Contaminated pixels were flagged as "blank" in each of the mosaics, and then filled in by extrapolating from surrounding pixels. The line rasters were then calibrated using the reported line strengths for Miller's (1974) position 1, corrected for reddening assuming $E(B-V) = 0.08$ (Parker 1967).

The final mosaics are shown in Figures 2 a-d. The rasters have been compressed by a factor of 3 to facilitate handling and display. The pixel size in the final rasters is 2.48 arcseconds. North is to the top of each figure and east is to the left. The bar has a length of 5 arcminutes = 1.1 pc at the assumed distance of 770 pc. The fact that the lines along which individual frames are joined are not apparent in the maps attests to the accuracy of the normalization of the frames.

Maps of the pixel by pixel ratios of [O III]/Hα, [O II]/Hα, and [O I]/Hα are presented in Figures 3 a-c, respectively. The displays are logarithmic. The histograms at the bottom of each figure show the log of the number of pixels which fell in a given display bin. The grey scale is labelled in units of $1000 \times \log_{10}(\text{line/Hα})$. The histogram covers a range of 2.44 in the log, or a factor of 277 in the ratio. The actual grey scale is compressed, and covers a factor of ~ 50 in the ratio. (For comparison, the color
scales in Figures 5 and 7 of HPD covered a factor of ~ 25 in the ratio.) As in HPD, ratios involving pixels for which one or the other raster had a value below a specified floor were judged unreliable. Such pixels are displayed as black in the ratio maps. Table 3 lists the flux values for these floors.

Truncation of portions of the rasters below floors hides the extension of cool lines into regions where [O III] is very weak and the extension of [O III] into regions where the cool lines are very weak. The relative extents of emission in [O III] and Hα can be seen in Figure 4, which is a color coded map showing the [O III] surface brightness (in red), the Hα surface brightness (in blue), and log([O III]/Hα) (in green). (The surface brightness resolution of Hα is very poor because only four bins were available for the display.)

III. Results and Discussion

A. Overall Comparison with the SE

The NE limb of the Cygnus Loop is quite similar in morphology and spectral characteristics to HPD’s Region I in the SE. While the impression from examining Figure 2 is that the [O III] emission is more filamentary and the cool lines (especially [O I]) are somewhat more diffuse, detailed
examination shows that most surface brightness features are in fact present in all lines. The general trend of stronger [O III] toward the eastern edge of the field and stronger [O I] toward the western edge noted in the SE is also preserved. This is apparent both in the trend in the [O III]/Hα ratio in Figure 3a and in the relative extent of the [O III] and Hα emission in Figure 4. The [O II]/Hα and [O I]/Hα ratios are much flatter than the [O III]/Hα ratio, and generally show less dramatic structure.

B. "Cool" Features

Two regions of emission are seen which are spectrally similar to HPD's Region IV (i.e., bright in [O I] and Hα, weaker in [O II], and essentially absent in [O III]). One of these regions appears as a clumpy, mottled area ~ .65 pc across, located in the west-central part of the field (subfield 4 in Figure 1). The appearance of the second region is quite extraordinary. It is a semicircular arc with a radius of curvature of ~ .2 pc, located in the NW part of the field (subfield 6). The arc is convex inward, as expected for a shock wrapping around a spherical clump. The arc bounds a region of diffuse emission, however, which extends inward from the arc toward the center of the Loop. This is the opposite of what is expected for a shock working into an isolated cloud, and suggests instead that the
surface of the shock at this location is a saddle-shaped portion of a larger sheet. By comparison with Raymond's (1979) models, shock velocities below ~ 50 km s\(^{-1}\) are required to account for the total lack of [O III] emission and the depression in the [O II]/H\(\alpha\) ratio at these locations.

C. Transition Through Feature Types

All of the feature types identified by HPD are present in the NE. Type I features are much more predominant than they were for the SE, which is as expected for the more extensive and apparently more evolved NE limb. The transition from type II to type I.5 to type I emission with distance behind the leading edge of the optical emission is not everywhere as clear as in HPD's Region 1, but is present to a degree.

The most striking example of the transition from type II nonsteady flow features to type I steady flow emission is the wedge of emission in the SE part of the field (subfield 3). This region stands out in the [O III]/H\(\alpha\) ratio map (Figure 3a) and to a lesser extent in the [O II]/H\(\alpha\) ratio map (Figure 3b). Much of the region was too weak in [O I] for reliable generation of ratios, and so does not appear at all in the [O I]/H\(\alpha\) map (Figure 3c). Inspection of the surface brightness maps in Figure 2 shows that this wedge is
indeed very bright in [O III], weakly present in [O II] and Hα, and partially absent in [O I]. Rather than occurring with increasing distance behind the edge of the emission, the transition from type II nonsteady flow features to type I steady flow features here occurs in roughly triangular zones, with the steady flow zone surrounded by nonsteady flow emission.

In Chapter 4 the interaction of a blast wave with a large cloud was discussed. In it, the transition to steady flow was described as occurring with distance inward into the cloud, away from the locus of intersection between the blast wave and the cloud. Figure 4.7c showed an oblique view of the "point" at the edge of a shocked cloud. In this case, the steady flow type I zone should be surrounded by a band of nonsteady flow type 1.5 and type II emission, in very good agreement with the observed structure of the [O III] wedge in the NE.

D. Profiles of Filaments

Figure 5 shows enlargements of a 2' 50" square field on the eastern edge of the optical limb (subfield I). Figure 5a shows the [O III] surface brightness in red and the Hα surface brightness in blue. Figure 5b shows the Hα surface brightness in blue and log([O III]/Hα) in green. Figure 6 shows an [O III] contour map of this region with a
separation between contour levels of $1.2 \times 10^{-4}$ ergs cm$^{-2}$ s$^{-1}$ sr$^{-1}$. Two filaments, designated A and B, are indicated in Figure 6.

From the enlargements in Figure 5 and the surface brightness maps in Figure 2 it can be seen that both of the filaments indicated in Figure 6 are type I. (i.e., they appear as features in all observed emission lines.) Along filament A the [O III] and Hα emission overlay each other exactly, and the filament appears only weakly in the [O III]/Hα map. Figure 7a shows surface brightness profiles across filament A for the four emission lines observed. The filament is very sharply peaked in all lines, with the central ridge about a factor of 2 brighter than the pixels on either side. The shapes of the profiles are all essentially identical, with the exception of a slightly suppressed peak in [O III]. The detailed agreement in the positions of the filament in all lines is as observed for type I features in the SE by HPD.

Filament B appears more strongly as a feature in the [O III]/Hα map than does filament A. Figure 5b shows a ridge in [O III]/Hα along the leading edge of the filament as defined by Hα, and a trough along the trailing edge of the filament. Figure 5a shows the cause of the ripple in the ratio. The [O III] filament appears as a red edge along the northeastern side of the Hα filament (which in turn appears as a blue edge along the southwestern side of the
[O III] filament). The offset between the filament as viewed in the two lines appears to be about a pixel width, or 2''6. If the offset between the positions of the filament as viewed in [O III] and Hα were removed, the peak and trough in the ratio of the two lines would disappear, and the filament would blend into the surrounding diffuse emission in the ratio map (as is typical of type I features). The [O III]/Hα map of the entire field (Figure 3a) shows a number of features which are similar to filament B.

Figure 7b shows surface brightness profiles across filament B. The peak in the profile shows a progressive shift between two adjacent pixel locations as the ion observed grows cooler. The width of the filament is approximately the same in all four lines, and is more than a factor of 2 greater than the point spread function of the images. Filament B is the first clear case in this or any study of an SNR filament for which the width of the recombination region is partially resolved. The progression of lines ([O III] + [O II] + Hα + [O I]) is in exactly the sense predicted by models of radiative shocks.

As noted in earlier chapters, for a $v_s = 100 \text{ km s}^{-1}$, $n_0 \approx 10 \text{ cm}^{-3}$, and $B_0 \approx 1 \mu\text{G}$, the cooling and recombination region should be $\leq 10^{16} \text{ cm (~ 1'')}$ thick. For Raymond's (1979) model $E$, for example (cosmic abundances and the parameters listed immediately above), the distance behind
the shock required for the flow to cool to $10^4$ K is $2.1 \times 10^{15}$ cm, and the distance required to recombine and cool to $10^3$ K is $5.6 \times 10^{15}$ cm. The resolution of a recombination region is reassuring rather than surprising, however. There are a variety of circumstances under which a cooling and recombination region can be considerably thicker than a few times $10^{15}$ cm, and some of these circumstances are almost certain to be present somewhere in the Cygnus Loop.

All of the ways to increase the scale for cooling and recombination behind a shock wave involve decreasing the ratio of the volume emissivity of the gas to the energy per unit volume in some part of the flow. As this ratio decreases, it requires the affected zone to be thicker in order to radiate away energy at the necessary rate.

One possibility is to deplete the gas of important coolants such as C, O, Si, and Fe. This would primarily affect the recombination region where far infrared lines of these elements are the dominant channel for cooling. This is not a likely explanation for the present observations, however, because it is not expected for abundances to change drastically within diffuse clouds over scales of a parsec or less.

For constant shock velocity, the energy per unit volume immediately behind the shock decreases as $n_0^{-1}$ while the cooling rate decreases as $n_0^{-2}$, so the thickness of the cooling region grows roughly in proportion to $n_0^{-1}$. A lower
$n_0$ does not drastically limit compression in the recombination region, however. As a result, reducing $n_0$ widens the gap between the shock and the recombination region, but does not have much affect on the thickness of the recombination zone itself. The flow in Raymond's model $N$ (cosmic abundances, $v_s = 100$ km s$^{-1}$, $n_0 = 1$ cm$^{-3}$, $B_0 = 0.01$ μG) takes $1.8 \times 10^{16}$ cm to cool to $10^4$ K, but only an additional $4 \times 10^{15}$ cm to recombine and cool to $10^3$ K. The profile of a shock moving into a low density medium should then show a broadened [O III] filament with some separation from the other lines. The separation between [O II], Hα, and [O I] should still be unresolved, however. This does not match the profile of filament B.

The magnetic field does not affect the flow until significant compression has occurred, and the magnetic pressure $B^2/8\pi$ equals the thermal pressure. At this point, however, the magnetic field supports the region, and no further compression occurs. Thus, magnetic pressure does not play a role in the cooling region where temperatures are of order $10^5$ K and densities only a few times $n_0$. Even the canonical interstellar field of 3 μG will eventually take over and support the recombination region for the shock velocities and densities being discussed, however. This will limit the cooling rate ($\propto n^2$) and broaden the region. The flow in Raymond's model Q (cosmic abundances, $v_s = 100$ km s$^{-1}$, $n_0 = 10$ cm$^{-3}$, $B_0 = 10$ μG) takes only $3 \times 10^{15}$ cm to
cool to $10^4$ K, but an additional $2.8 \times 10^{16}$ cm to recombine and cool to $10^3$ K.

At the distance of the Cygnus Loop, the profile of a shock such as described by Raymond's model Q would have an unresolved cooling region, but a recombination region with a thickness of $\sim 2''5$. This is in excellent accord with the observations of filament B. The surface brightness of the filament also favors field limited compression over low preshock density as an explanation for the differences in filament B in different emission lines. The peak [O III] surface brightness of the profile in Figure 7b is $3.75 \times 10^{-4}$ ergs cm$^{-2}$ s$^{-1}$ sr$^{-1}$, and the length of the filament is about $40'' = 4.6 \times 10^{17}$ cm. Comparison with Raymond's model Q ($n_0 = 10$ cm$^{-3}$, $B_0 = 10$ $\mu$G) gives a brightness of 18 FOS (face-on shocks). This agrees well both with observations of the SE (HPD) and with the calculations of sheet geometries in Chapter 4 of this thesis. Comparison with Raymond's model N ($n_0 = 1$ cm$^{-3}$, $B_0 = .01$ $\mu$G) gives a brightness of 170 FOS, which would require that the geometry of the filament be $\sim 10$ times deeper than its apparent length. This is much too large by comparison with the previous discussions of filamentary structures in this thesis.
\textbf{TABLE 5.1}

\textbf{Field Centers}

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3 & 20 54 37.9 & +31 29 15 \\
4 & 20 53 55.2 & +31 33 05 \\
5 & 20 54 46.9 & +31 25 25 \\
6 & 20 53 41.7 & +31 36 55 \\
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<td>25/26</td>
<td>45m</td>
<td></td>
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<tr>
<td></td>
<td>27/28</td>
<td>45m</td>
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<tr>
<td>[O I] 6300Å/6Å</td>
<td>22/23</td>
<td>60m</td>
<td></td>
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<td></td>
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<tr>
<td></td>
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<td>60m</td>
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<tr>
<td>Hα 6562Å/11Å</td>
<td>22/23</td>
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<td>24/25</td>
<td>50m</td>
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<tr>
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<td>30m</td>
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<tr>
<td></td>
<td>26/27</td>
<td>45m</td>
<td>Passing Clouds</td>
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<tr>
<td>Contin. 6002Å/104Å</td>
<td>27/28</td>
<td>5m</td>
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<td>5m</td>
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¹Dates refer to August 1983.
### TABLE 5.3
Floors for Generation of Ratios

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<th>Raster</th>
<th>Floor ((10^{-5} \text{ ergs cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1}))</th>
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<tr>
<td>[O III] (\lambda 5007)</td>
<td>1.80</td>
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<tr>
<td>[O II] (\lambda 3727)</td>
<td>12.00</td>
</tr>
<tr>
<td>[O I] (\lambda 6300)</td>
<td>0.90</td>
</tr>
<tr>
<td>H(\alpha) (\lambda 6563)</td>
<td>2.16</td>
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</table>
FIGURE CAPTIONS

Figure 5.1. Nomenclature for the six individual CCD fields combined to generate mosaic rasters of the Cygnus Loop NE.

Figure 5.2. Linear gray scale displays of (a) [O III], (b) [O II], (c) [O I], and (d) Hα surface brightness rasters for the NE limb of the Cygnus Loop. Each raster is a mosaic of six CCD frames obtained with the KPNO 0.9-m CCD direct camera. Bright stars have been suppressed. The bar shows a scale of 5 minutes of arc, \( \approx 1.1 \) pc at an assumed distance of 770 pc.

Figure 5.3. Grey scale maps of the log of the pixel by pixel line ratios for (a) [O III]/Hα, (b) [O II]/Hα, and (c) [O I]/Hα. Pixels for which one or the other line were below a floor set for generation of reliable ratios are not plotted.

Figure 5.4. Color coded map of the [O III] surface brightness (red), the Hα surface brightness (blue), and \( \log_{10}([O \text{ III}]/H\alpha) \) (green).

Figure 5.5. Enlargement of a 2' 50" square field along the eastern edge of the NE limb (subfield 1). Figure 5a
shows the [O III] surface brightness in red and the Hα surface brightness in blue. Figure 5b shows \( \log([O \text{III}]/H\alpha) \) in green and the Hα surface brightness in blue.

**Figure 5.6.** [O III] contour map of the field shown in Figure 5. The filaments marked A and B are discussed in the text. The contours are linear, with a spacing of \( 1.2 \times 10^{-4} \) ergs cm\(^{-2}\) s\(^{-1}\) sr\(^{-1}\).

**Figure 5.7.** Surface brightness profiles across filaments A (Figure 7a) and B (Figure 7b), indicated in Figure 6. Moving from left to right along the profiles is moving from north and east to the south and west across the filaments. The numbers on the vertical axes give surface brightness scales in units of \( 10^{-4} \) ergs cm\(^{-2}\) s\(^{-1}\) sr\(^{-1}\). Scales for [O III] and Hα are given on the left side of the figures, and scales for [O II] and [O I] are given on the right.
Figure 5.1
Figure 5.5a

Figure 5.5b
Figure 5.7a
Figure 5.7b
CHAPTER 6

SUMMARY AND OVERVIEW

I. Overview

This thesis has presented a variety of data and has addressed a number of astrophysical problems associated with the Cygnus Loop. This chapter presents a brief recap of the data presented, lists a few of the most important specific observational results, and summarizes some of the most significant conclusions drawn.

Before recapping specific aspects of the thesis, however, it should be noted that this work is unified by more than the selection of a common object for study. The underlying goal throughout has been to establish a framework for understanding the entire range of observations of the Cygnus Loop. This goal seems to have been achieved. The picture of the Cygnus Loop which emerges is that of an adiabatic (but probably not evaporative) remnant evolving into a medium with $n_0 \approx 0.1 \text{ cm}^{-3}$, containing clouds with densities $\leq 10 \text{ cm}^{-3}$ and a characteristic size of a few parsecs. Careful consideration of the appearance of such a remnant shows that the \textit{ad hoc} scenarios which have been
invented to account for various observations (e.g., the use of small cloudlets to explain the existence of nonsteady flow emission and differences in the structure when viewed in different emission lines) are not necessary. This is a very pleasing result because it allows the Cygnus Loop (and presumably other SNRs) to evolve in an interstellar medium similar to that inferred to exist on the basis of a range of other observations.

II. Summary of Masters Work

The results presented in this thesis were built upon groundwork laid in the author’s Masters thesis, entitled "Digital Analysis of Narrow-Band Imagery of the Cygnus Loop," and published by HPD. That work presented calibrated image tube data taken in the light of emission from six different ionic species for a field on the SE limb of the Cygnus Loop, and was the first detailed investigation of the relationship between the spectral properties and morphology of the optical emission. The major results of that work which are most relevant to the current research are summarized as follows:

1. Features can be classified into types on the basis of their presence or absence in various emission lines. Feature types correspond to varying degrees of completeness
of cooling and recombination regions behind radiative shock waves.

(2) Spectral characteristics of shocks which are judged to be steady flow on the basis of feature type are not at odds with shock model calculations.

(3) Differences in the structure of the emission when viewed in different emission lines are due to a transition through feature type followed by decreasing shock velocity with increasing distance behind the edge of emission. The spatial scale for the transition from type II to type I emission is comparable to the differential velocity between the blast wave and radiative shocks times the time required to establish steady flow.

(4) The existence of steady flow shocks makes the existence of small cloudlets in the preshock medium unlikely.

(5) The diffuse emission between filaments is spectrally similar to the filaments themselves. This, combined with the fact that filaments are much brighter than face-on shocks, suggests that they are due to projection effects.

III. Summary of Observational Data

The following new data have been presented:

(1) A high resolution comparison of the soft X-ray
emission and the optical emission for a field in the SE region of the Cygnus Loop;

(2) A map of the electron temperature in the SE inferred from imagery in the lines of [O III] \( \lambda 5007 \) and [O III] \( \lambda 4363 \); and

(3) CCD imagery of the NE in the light of emission from four ionic species which span the entire recombination zone behind radiative shocks.

IV. Summary of Major Observational Results

A number of statements can be made to describe the most significant specific observational results:

(1) A sharp escarpment in the X-ray surface brightness follows an edge of young optical emission for over a parsec.

(2) The brightest X-ray emission in the Loop is found just inside young optical emission. In general, bright X-ray emission appears to come from slabs just interior to the locus of optical emission.

(3) Older, more evolved regions of optical emission are not exceptionally bright in X-rays.

(4) The pressure of the X-ray emitting gas in the Loop varies by at least a factor of 6.

(5) An [O III] arc, judged to be a shock with an extremely incomplete recombination zone on the basis of
feature type as defined by HPD, is observed to have a
temperature which is also too high for steady flow.

(6) A type I filament is identified in which the
recombination region is begun to be resolved.

(7) A region is observed in the NE in which the
transition from nonsteady flow to steady flow emission
occurs laterally with respect to the radial direction.

V. Summary of Major Conclusions Regarding the Structure of
and Physical Processes in the Cygnus Loop

Important specific conclusions drawn include:

(1) With the possible exception of the break-out in
the south, the Cygnus Loop is not evolving into a diffuse
hot matrix as described by the McKee and Ostriker (1977)
theory of the ISM. The Cygnus Loop is similarly not a
supernova remnant such as described by Cowie, McKee, and
Ostriker (1981) (e.g., Section 2.IV.E).

(2) Clouds around the Cygnus Loop range in size from
about a parsec to about 10 parsecs, and are fairly smooth
internally on scales < 10^{17} cm (e.g., 2.IV.B, 4.II.C).

(3) Evaporation does not play a dominant role in the
X-ray emissivity of the gas in the remnant (at least for the
bright regions observed in detail) (2.IV.C).

(4) The relationship of the X-ray and optical
emission, as well as the overall structure of the Loop at X-
ray wavelengths, can be explained by the combined effects of variations in the preshock density (leading directly to variations in the postshock density behind the adiabatic blast wave) and inertial pressurization of the X-ray gas behind portions of the blast wave which are forced to decelerate rapidly (2.IV.D).

(5) The appearance of optical emission interior to the edge of the X-ray shell is nothing more than a projection effect arising from a shell which is complete in X-rays and incomplete in optical emission. The clouds containing radiative shock waves have for the most part not been engulfed by the blast wave. The bright optical filaments are the local outer boundary of the remnant (e.g., 2.III.C).

(6) The expected relationship between nonsteady flow and temperature inferred from [O III] line strengths does exist (3.IV.C).

(7) Filaments in the Cygnus Loop are small portions of very large contiguous sheet-like shock fronts which are seen edge-on. The overall morphology of the emission arises naturally from projection effects in bumpy sheets (4.III.B).

(8) The presence of nonsteady flow shocks is due primarily to the time that it takes to establish a complete recombination region behind a portion of the shock front which has only recently encountered a cloud (e.g., 2.III.D).

(9) The observed spatial variations in spectral characteristics of the optical emission result from
variations in completeness and shock velocity with distance from the edge of a cloud (4.III.E).

(10) The velocity profiles of filaments can be explained simply as projection effects in the accelerated sheets of material behind shock fronts. The sheet geometries inferred from the shapes and sizes of observed filaments predict surface brightnesses and velocity profiles for filaments which are in very good agreement with observation (4.II, 4.III.A.ii, 4.III.C).

(11) The basic conclusions drawn for the SE by HPD appear to hold for the NE as well (5.III).

VI. Ongoing Research

The work begun in this thesis is far from complete. With a basic theory of what the Cygnus Loop is (and is not) in hand, it is now possible to ask some very specific questions about the processes occurring in the Cygnus Loop and to use the Cygnus Loop as a model for comparative studies of other remnants. The author is involved in a number of such projects which are currently underway. Among these is an attempt to construct a detailed model of the structure of the HPD "spur" and the surrounding region which accounts for the surface brightness structure, optical and UV spectra of positions along the spur, echelle spectroscopy of the region, and the morphological relationship of the
spur to surrounding emission. Time has also been obtained with the International Ultraviolet Explorer satellite to observe the vicinity of XA.

Another project is to make detailed comparisons between X-ray and optical maps of other portions of the Loop to see how well the conclusions of Chapter 2 of this thesis generalize. The radio map of Straka et al. (1985) will be included in the analysis for the NE, providing for the first time analysis of quantitative high resolution imagery in radio, X-ray, and optical bands. The encounter between a blast wave and a cloud is being investigated using a hydrodynamic model code in order to better quantify the effect of inertial pressurization on X-ray emissivity.

Finally, it should be mentioned that imagery of the HPD "spur" will be part of the "guaranteed time" observing program to be conducted with the Wide Field and Planetary Camera on Space Telescope. These observations will resolve the structure of the cooling and recombination regions, and will provide information about the applicability of shock model calculations, the growth of recombination regions with increasing column depth through the shock, the geometry of the shock front, the structure and preionization of the ISM in advance of the shock, and the effects of magnetic fields and thermal instabilities on the flow.
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