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DIGITAL ANALYSIS OF NARROW BAND
IMAGERY OF THE CYGNUS LOOP

by

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Abstract

Digital analysis of narrow passband direct imagery of a field in the southeast part of the Cygnus Loop SNR is presented. Calibrated surface brightness and spectral line ratio maps involving emission lines from six different ionic species are shown. The detailed morphology of the remnant and correlations between various line ratios are discussed in the context of recent shock model calculations. The spatial structure is categorized on the basis of the presence or absence of features in images isolating different emission lines, and the correlation or lack thereof between these features and features in the maps of spectral line ratios such as $[O\ III] \lambda 5007/H\alpha$. For a common type of structure, features present in line ratio maps are not associated with surface brightness features. These same structures also demonstrate spectral behavior consistent with that predicted by steady-flow shock calculations, indicating the presence of steady-flow shocks with velocities from $\lesssim 60$ km/sec to ≈ 120 km/sec. Differences in the morphologies of the remnant as viewed in different emission lines and gradients in spectral line ratios are interpreted as a continuous transition with distance behind the blast wave from non-steady-flow shocks with velocities $\gtrsim 130$ km/sec to steady-flow shocks with velocities ≈ 60 km/sec.

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Foreward

This thesis is, with very slight modification, a paper submitted to the Astrophysical Journal, under the authorship of J. Jeff Hester, Robert A. R. Parker, and Reginald J. Dufour. As such, no clear distinction is drawn in the text between my part in the paper, and that of Drs. Parker and Dufour. I received the data in the form of magnetic tapes of linear surface brightness arrays, and performed all reductions (as described in the text) which were done using the Rice University Picture Processing System (including writing the majority of the software used in those reductions). The presentation of the data and its interpretation are largely my own, with advice, direction, and suggestions from Drs. Parker and Dufour as is appropriate for thesis advisors. The writing of the paper was mine, but was subject to detailed review and contains revisions made at their suggestion.

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I. Introduction

The Cygnus Loop is a large ring of emission line nebulosity with a diameter of approximately 3° , which has for some time been understood to be a supernova remnant in the middle to late stages of its evolution. Its large apparent size and high surface brightness make it ideal for the study of this class of object. By comparing observations of the proper motions of filaments at the edge of the nebula with the radial velocities of features nearer to the center of the Loop, Hubble (1937) estimated a distance to the Cygnus Loop of 770 pc. While this number is somewhat uncertain (Kirshner, 1976), it is accurate enough to provide a reasonable idea of the actual physical scale of the observed features. Parker (1967) found that the extinction in the direction of the Cygnus Loop is also low ($E(B-V) \sim 0.08$ mag), which minimizes the difficulties in interpreting spectrographic observations. For these reasons it has been the object of extensive study in optical (e.g., Parker, 1967; Miller, 1974; Fesen et al., 1982), UV (e.g., Benvenuti et al., 1980; Raymond et al., 1980), radio (Keen et al., 1973; Dickel et al., 1980), and X-ray (e.g., Rappaport et al., 1979; Gronenschild, 1980) wavelengths.

It was originally suggested by Cox (1972) that the Cygnus Loop is an old SNR in the "snowplow" phase of its evolution. More recent observations, particularly in X-ray wavelengths, suggest that it is more likely in the adiabatic phase of its evolution in which the envelope of the remnant is composed of a 300-400 km/sec blast wave in a medium with densities of $.1-1 \text{ cm}^{-3}$. Such a blast wave would drive shocks with velocities of approximately 100 km/sec into a medium of density $2-10 \text{ cm}^{-3}$. These slower shocks in a denser medium would have the right

properties to produce, at least in a qualitative sense, the observed optical emission (McKee and Cowie, 1975).

In recent years advances in the understanding of the atomic physics of the ISM have led to a new generation of models of the propagation of shock waves in the ISM (e.g., Cox, 1972; Chevalier, 1974; Dopita, 1979; Raymond, 1979). All of these models have for the sake of simplicity assumed that the shocks have reached a state of "steady-flow" in which the entire recombination region behind the shock has had a chance to form. An important result of these models is that the thickness of the recombination region is generally quite small — on the order of a few times 10^{15} cm. A recombination region of this size is below the limits of resolution of current optical techniques even at the distance of the Cygnus Loop (10^{15} cm $\approx$ 0.1 arcsecond at $d = 770$ pc). This implies that the observed structure of the Cygnus Loop ([O III] brighter on the outside of the Loop and lines from lower ionization species such as [O I] and [S II] brighter on the inside of the Loop) cannot be attributed simply to an extended recombination region behind a shock.

Spectral observations of the Cygnus Loop have often been used in attempts to match the predictions of these steady flow models, assuming that the observations represent emission integrated over entire recombination regions. For example, Miller (1974) looked at three locations and found that his observations agreed in an order of magnitude sense with Cox's (1972) models, assuming depleted abundances. Raymond (1979) was able to achieve somewhat better agreement with Miller's observations by fine tuning the parameters of three of his models.

In general, however, the success with which models and observations have been made to agree has been less than ideal. In particular, lines

of [O III] are often seen to be much stronger than predicted in comparison with H β and other lines. In part, problems in matching model calculations and observations may be due to effects such as the presence of shocks of several different velocities in the aperture of the spectrograph (Benvenuti et al., 1979). There also remain inadequacies in the input physics of the models. For instance, Butler and Raymond (1980) show that the effects of charge transfer, which were not adequately dealt with in previous models, can significantly reduce the degree of ionization for much of the recombination region. The destruction of grains by the shock and its influence on abundances is also a process discussed by several authors (e.g., Benvenuti et al., 1979; Raymond, 1981; Draine and Salpeter, 1979). This process could significantly affect some elements such as oxygen (for slower shocks — $v \approx 100$ km/sec) and carbon and silicon (for faster shocks — $v > 200$ km/sec) in ways not clearly understood. UV observations made with the IUE (Raymond et al., 1980; Raymond, 1981) indicate that optical depths for UV resonance lines may become quite large, which complicates the treatment of radiative transfer in the models. The idea that the assumption of steady flow is invalid has also gained recent popularity (Raymond et al., 1980; Fesen et al., 1982). In particular, Fesen et al. suggest that the discrepancies between models and observations are extremely serious, and that in fact the assumption of steady flow is seldom if ever satisfied. Recent models also have a large number of free parameters (other than pre-shock density and shock velocity) which affect the predicted spectrum and prohibit the thorough mapping of the shock parameter space with models. As a result, shock parameters derived from spectral characteristics are somewhat ambiguous.

In the present paper, we present results of digital analysis of narrow band interference filter photographs of an area on the southeast side of the Cygnus Loop. In using this method, we are essentially doing spectrophotometry with a spatial resolution of ~ 3 arcseconds on a preselected set of emission lines. The relatively large amount of spatial data acquired by direct imagery allows us to study in detail both the monochromatic surface brightness structure of the nebula and the spatial variations of line ratios, as well as the correlations between different line ratios as a function of position. In Section II we present our observations and discuss at some length the procedures and errors involved in the reduction of the data. In Section III we present our data and the results of our observations, attempting only a minimum of interpretation. In Section IV we discuss our data in the context of theoretical models and current difficulties in interpreting supernova remnant spectra and morphology. Section V contains a brief summary of the more significant points of the paper.

II. Observations and Data Reduction

A. Generation of Calibrated Rasters

Observations of a portion of the Cygnus Loop approximately 18 arcminutes in diameter were made by one of us (Parker) and T. Gull during 1973-74 using the Carnegie Image Tube direct camera on the Number 1 0.91-m f/7.5 telescope at Kitt Peak National Observatory. This system uses an RCA 33063 two stage image tube, whose output phosphor is imaged onto baked IIIa-J plates. Observations were made at the wavelengths of emission lines of six different ionic species, and at a continuum wavelength. Table 1 gives the specifications on the filters used for the plates, and Table 2 lists the exposure times. Appropriate sensitometer plates were also exposed and developed with the image tube plates for calibration of the intensity-density relationship for each plate. The plates were digitized using the PDS microdensitometer at KPNO in 1900×1900 pixel arrays using a 20 micron square aperture (corresponding to 0.6 arcseconds) with 20 micron steps between measurements. Characteristic curves were then fit to calibration plate spots, and density to intensity conversions were done. The initial rasters were then compressed by a factor of two in both directions to generate rasters with a pixel size of 40 microns, or 1.2 arcseconds. All remaining processing was done using the Rice University Picture Processing System, consisting in part of a PDP 11/55 computer and a $512 \times 512 \times 8$ bit color image display. For processing and displaying convenience a subarray of the entire 950×950 pixel frame was selected for further processing. These final rasters have a size of 512×260 pixels ($10'14'' \sim \text{E-W} \times 5'12'' \sim \text{N-S}$; $\sim 2.25 \text{ pc} \times 1.14 \text{ pc}$ at a distance of 770 pc). The

Table 1
Filter Characteristics

Line	Wavelength	FWHM
[O II]	3722 Å	20 Å
H β	4862	30
[O III]	5007	16
[O I]	6301	6
H α	6562	11
[N II]	6585	11
[S II]	6720	27

Table 2
Exposures

Line	Plate No.	Exposure Times
[O II] $\lambda\lambda 3727$	2544	60 min
	2560	15
H β	2539	60
[O III] $\lambda 5007$	2543	3
	2561	15
[O I] $\lambda 6300$	2575	120
H α	2545	60
	2546	15
[N II] $\lambda 6584$	2578	55
[S II] $\lambda\lambda 6725$	2562	30
	2563	10

horizontal direction in the rasters is inclined at an angle of -1.05° with respect to the east-west direction. The area observed is located along the southeastern edge of the Cygnus Loop (Figure 1), and includes Miller's (1974) position 2. The field of the final rasters is centered at $\alpha(1981) = 20^{\text{h}}56^{\text{m}}19^{\text{s}}.2$ and $\delta(1981) = 31^\circ30'38''$.

For each single-plate raster 10 to 12 sky positions were chosen which were seemingly free of stars and nebulosity. The residual surface brightnesses at these sky positions were averaged, and the averaged sky value for each plate was then subtracted from every pixel in that raster. The spread in sky values obtained across the field was generally less than 15-20% of the minimum nebular surface brightnesses used, and so this procedure was adequate. For the long exposure plates the image tube thermal background was higher and more uneven. Since no dark exposures were made, it was not possible to accurately map the thermal background, so there remains a non-uniform background in some of the rasters from longer exposure plates. We believe that this problem is really only significant for the raster from the [O I] $\lambda 6300$ plate, which has a background which changes by an amount comparable to the minimum object surface brightnesses used in the generation of pixel by pixel ratios.

The rasters were aligned relative to each other by measuring the positions of 70 stars using an iterative centroid finding algorithm, then deriving coordinate transformations from each plate to the 4400 Å continuum plate using a least squares fit to a 12 parameter polynomial. Each raster was then transformed onto the standard raster using these mappings. The size of the corrections for alignment errors was generally less than 3 pixels. Judging by the errors of the fit, the

Figure 1. Map of the Cygnus Loop, based on plates taken by R. A. R. Parker with the Palomar 1.2 m Schmidt. The circle shows the field of the image tube plates. The field discussed in this paper is indicated by the box.

final error in alignment is $< .25$ pixel or $.3$ arcseconds. This is sufficiently smaller than the seeing limited resolution (~ 3 arcseconds) that alignment errors are of no significance.

A substantial reduction in noise was achieved with little reduction in real resolution by filtering and smoothing the data using a 3×3 pixel window, thus making the resolution of the rasters match the $\sim 3-4''$ resolution of the plates themselves. Coadding of rasters of the same wavelength was done, where more than one plate exists, by normalizing the files to be coadded to each other, then weighting the data according to its quality, as judged by its position on the photographic characteristic curve for a given plate. A weight of $.01$ was assigned to values on the extreme toe or shoulder of the curve, with a weight of 1 assigned to values on the linear portion of the curve, and a weight of 0.75 assigned to values on the beginning of the shoulder. If the pixel was weighted at $.01$ in both rasters being coadded, the pixel in the output raster was set to a blank. The final coadded raster has the full dynamic range of the combination of both plates used. This is achieved by effectively using the long exposure plates for the faintest regions and the short exposure plates for the brightest regions. Additional noise reduction was also obtained in regions where data from both sources were good. The locations of pixels corresponding to star locations were mapped using the continuum plate, and these pixels were set to blanks.

For the rasters of all lines except $[O\ I] \lambda 6300$, calibration into absolute surface brightness units was done using Miller's (1974) spectrophotometry for his position 2. His slit position was mapped onto our rasters and the values of pixels which fell in his aperture were

summed. (We refer to this procedure as "raster spectrophotometry.") The [O I] raster was calibrated in a similar fashion using observations of a bright [O I] knot in the western part of the field. The observations were made by two of us (Hester and Dufour) in April 1982 using the Intensified Reticon Scanner with the White Spectrograph on the No. 1 0.91-m telescope at KPNO. These observations were reduced using the standard reduction routines at KPNO, and corrected for reddening using $E(B-V) = 0.08$. Table 3 gives measured fluxes $F(\lambda)$ and reddening corrected fluxes $I(\lambda)$ for this location. Also given are the results $I_r(\lambda)$ of "raster spectrophotometry" of this location, done on the rasters calibrated using Miller's data. The last column in Table 3 gives the absolute value of the difference $\Delta I(\lambda) = I(\lambda) - I_r(\lambda)$, divided by the average of $I(\lambda)$ and $I_r(\lambda)$.

Figure 2 shows H α and [O III] $\lambda 5007$ direct image tube photographs with the positions of Miller's slit and the slit used for our 1982 photoelectric observations, along with additional locations for "raster spectrophotometry" and slices to be used in later sections. Figure 3 shows the same locations overlaid on a grey scale map of the log of the [O III] $\lambda 5007$ /H α ratio. Figure 2 also marks the locations of several stars with known coordinates. Table 4 gives the positions of these stars in right ascension and declination, as well as in our field coordinates. Also listed are field coordinates for the locations of "raster spectrophotometry" and the slices shown in Figures 2 and 3. Field coordinates (in units of pixels) are defined going to the right and down from the top left hand corner of the field. Number pairs of the form (x,y) in the text and tables refer to these coordinates.

Table 3

IRS Data

<u>Photoelectric Spectrophotometry</u>			$I_r(\lambda)$	$\frac{ \Delta I(\lambda) }{\langle I(\lambda) \rangle}$	
λ	$F(\lambda)$	$I(\lambda)$	From Rasters		
3727	500	537	460	15%	
4861	100	100	100	-	
5007	52	51	46	10%	
6300	196	181	Used for Calibration	-	
6563	346	317		301	5%
6584	261	239		201	17%
6725	443	403		420	4%

Figure 2. [O III] $\lambda 5007$ and $H\alpha$ plates of the field observed. Locations of slices (S1 through S6) for spatial profiles, positions for "raster spectrophotometry" (1 - 16; See Table 5), and stars with known coordinates (Table 4) are indicated. S1 is the location of Miller's (1974) position 2, used in calibration of the rasters. Our (1982) IRS slit was positioned E-W through location 9.

Figure 3. Logarithmic grey scale $[O III] \lambda 5007 / H\alpha$ ratio map. Labels on the scale are logarithms. Logs < -0.6 are black. Logs > 0.8 are white. Areas with excessively faint emission are black. Data "floors" for generation of pixel to pixel ratios are not enforced. Locations of slices and "raster spectrophotometry" are indicated as in Figure 2.

Table 4

Coordinate Reference Stars			
Star	$\alpha(1981)$	$\delta(1981)$	Field Coordinates
A	20 ^h 56 ^m 15 ^s .3	+31° 04' 39"	(294.8, 79.8)
B	20 ^h 56 ^m 06 ^s .6	+31° 03' 58"	(388.9, 110.1)
C	20 ^h 55 ^m 58 ^s .4	+31° 03' 13"	(472.1, 145.8)

Locations of "Raster Spectrophotometry"			
Location	Field Coordinates	Location	Field Coordinates
1	(69, 62)	9	(486, 113)
2	(416, 185)	10	(332, 111)
3	(270, 181)	11	(381, 160)
4	(372, 198)	12	(51, 81)
5	(393, 157)	13	(54, 120)
6	(425, 148)	14	(91, 113)
7	(346, 166)	15	(491, 145)
8	(364, 168)	16	(292, 144)

Endpoints of Slices		
Slice	Begin	End
S1	(401, 142)	(435, 185)
S2	(28, 91)	(163, 2)
S3	(233, 219)	(228, 134)
S4	(47, 193)	(122, 194)
S5	(69, 181)	(168, 90)
S6	(412, 176)	(343, 219)

Figures 4 and 5 show grey scale maps of the log of the surface brightness for all lines observed. The log format was chosen because it makes visible both faint and bright structure. The scale labels are logs of the surface brightness, where the unit of surface brightness is 10^{-9} ergs cm^{-2} s^{-1} sr^{-1} . (For example, a label of 2.0 implies a surface brightness of $10^{2.0} \times 10^{-9} = 10^{-7}$ ergs cm^{-2} s^{-1} sr^{-1} .) The reader may find it useful to compare the direct photographs in Figure 2 with the $\text{H}\alpha$ and [O III] maps in Figure 5. Figures 6 and 7 show a number of color coded maps of the logarithms of various ratios of emission lines. All of these figures are overlaid with a grid of size 50 pixels (1 arcminute or .22 pc at a distance of 770 pc). The color coded maps use three different scales. The color scale ranging from red to purple is used to map pixels where the data in both files were above floors which were defined to eliminate data which were too weak for generation of reliable pixel to pixel ratios. (The noise in ratios at low surface brightness results from imperfect sky subtraction and noisy weak emission.) Each color step corresponds to a factor of 1.26 in the ratio (= 0.10 dex in the log). Labels on the displayed color scales are logs of the ratio. The black and white grey scale is used to map the logarithm of the surface brightness of the numerator in the ratio when the denominator is below its floor (i.e., is too weak to produce a reliable ratio), and the green grey scale is similarly used for the surface brightness of the denominator when the numerator is too small for generation of a good ratio.

Figure 4. Logarithmic grey scale [O III] $\lambda 5007$ and H α surface brightness maps. Labels at the top and bottom of the grey scale are $\log$ (surface brightness), where the unit of surface brightness is 10^{-9} erg $\text{cm}^{-2} \text{s}^{-1} \text{str}^{-1}$. A 50 pixel = 1 arcminute grid is overlaid onto the maps to facilitate comparison with other surface brightness and ratio maps. The grid originates at the origin of the field coordinates in the upper left (NE) corner of the field.

Figure 5. Logarithmic grey scale surface brightness maps for $[O\ III] \lambda 3727$, $[N\ III] \lambda 6584$, $[S\ II] \lambda 6725$, and $[O\ III] \lambda 6300$ (see Figure 4).

Figure 6. Logarithmic map of the $[O\ III]\ \lambda 5007/H\alpha$ ratio. The color scale ranging from red to purple is used to map the ratio where the surface brightnesses of both lines are high enough for generation of reliable pixel by pixel ratios (i.e., are above floors established to eliminate noisy weak emission and values affected by imperfect sky subtraction). Dullest red pixels have $\log([O\ III]\lambda 5007/H\alpha)$ less than the value at the red end of the comparison scale. Extreme purple pixels have $\log([O\ III]\lambda 5007/H\alpha)$ greater than the value at the purple end of the scale. Each color step represents a factor of 1.26 in the ratio = 0.1 dex in the log. The white grey scale maps $\log$ (surface brightness) for the numerator ($[O\ III]$) when the denominator ($H\alpha$) is below its floor for generation of reliable ratios. The green grey scale maps the log of the denominator when the numerator is below its floor. The 50 pixel = 1 arcminute grid allows comparison with other maps (see Figure 4).

Figure 7. Logarithmic maps of the $[O\ III] / [O\ II]$, $[O\ III] / H_{\alpha}$, $[O\ II] / [O\ III]$, and $[O\ III] / [O\ II]$ ratios (as in Figure 6).

B. Error Analysis of Ratio Data

Figure 8 shows profiles of the log of the $H\alpha/H\beta$ ratio along several different slices. These profiles, and others like them to be discussed in later sections, were generated by sampling the data with a pixel sized square aperture at 1.2 arcsecond intervals along a slice. The pixel sized aperture was used to determine the fractional weight of the sampled pixels and derive an interpolated value for the location of the aperture center. As with other presentations of pixel by pixel ratios, points are suppressed if either or both of the lines have surface brightnesses below their respective floors. The positions of these slices are marked on Figures 2 and 3 as S1, S2, etc. The arrows point from the left end to the right end of the slices, as plotted in Figure 8 and in similar figures to be presented later.

The $H\alpha/H\beta$ ratio is useful in analysis of both large and small scale errors in the line ratio data because the Balmer decrement should not vary by more than $\sim 5\text{--}10\%$ for spectra of recombining shocked gas (Raymond, 1979). Spatial variations in reddening for the Cygnus Loop also seem to be small (Parker, 1967, Fesen et al., 1982), and the $H\alpha/H\beta$ ratio is in fact observed to be relatively constant (Fesen et al., 1982). As a result, the primary sources of high frequency spatial variations in maps of this ratio should be statistical noise and wavelength dependent inhomogeneities in sensitivity across the face of the photocathode of the image tube. The ratio shows a systematic change from the east side of the field to the west, going from values of ~ 2.5 to values of ~ 3.3 . This range of values is comparable to the range of values for this ratio reported for other locations in the Cygnus Loop by Fesen et al. (1982), and may be due to a change in reddening across the

Figure 8. Spatial profiles of $\log(H\alpha/H\beta)$ along slices (S1-S6) indicated on Figures 2 and 3. Large ticks show reference levels ($H\alpha/H\beta = 3$) for each profile. Small ticks indicate changes of 0.125 dex in the log (= a factor of ~ 1.3 in the ratio). Ticks along the horizontal axis indicate position along the slice. Gaps in the profiles are due to data below floors for generation of pixel by pixel ratios.

field of $\sim .05$ mag. Since possible spatial variations in the reddening correction were not taken into account in the calibration of the other rasters, this introduces a further slight systematic error, but one which is no larger than the statistical noise in the data. In Figure 8 where both rasters are well exposed (have values above the "floors" assigned in the processing as discussed above), the $H\alpha/H\beta$ ratio shows high spatial frequency variations of $\sim .05$ dex (= 10-15% in the ratio) over scales of 5-10 arcseconds. We take this to be indicative of the overall high frequency system noise in line ratios. This estimate is borne out by examination of the ratios of rasters from two different plates of the same wavelength where pixel values from both rasters were from the linear portion of their respective characteristic curves.

As mentioned previously, floors are established for each raster, below which values are not used in generation of pixel by pixel ratios. Besides avoiding difficulties with the sensitivity of ratios to inaccurate sky subtraction and noisy weak data, these floors also help avoid problems when final rasters are taken from single plates where possibly significant errors may exist on the toes of the characteristic curves. The problems on the shoulder of the curve remain, but are only significant for very large data values. Based on comparisons of similar regions in long and short exposure plates taken in the same wavelength, these errors are not likely to be greater than 15%.

Other potential sources of systematic errors exist. The problem with thermal background has already been discussed. A related problem arises from possible inhomogeneities in the image tube sensitivity across the face of the photocathode. Such inhomogeneities could possibly even be wavelength dependent. Since flat field exposures were not

made, it was not possible to map these inhomogeneities. However, since all exposures were made with identical placement of the object on the tube, this effect should cancel to first order. The extremely flat $H\alpha/H\beta$ ratio also strongly suggests that variations in the photocathode sensitivity are not strongly wavelength dependent. No effort was made to subtract continuum emission, but this is theoretically expected to be insignificant for a recombining collisionally excited gas. This is substantiated by the faintness of nebular features on continuum plates.

A final possible source for systematic errors in line ratios is in the calibration of the rasters. Miller's uncertainties are $\sim 20\%$ in absolute $H\beta$ flux and $\sim 15\text{--}25\%$ for relative fluxes. His slit is also located in a very chaotic region, so a slit placement error could lead to an error in our calibration. By moving the placement of our reconstruction of his slit by two pixels in each direction, we estimate the order of this error to be $10\text{--}15\%$ in relative line strengths, and slightly greater in absolute flux. "Raster spectrophotometry" at the location of our IRS slit was done on the rasters which were calibrated using Miller's data (as described above — see Table 3). The relative line strengths measured from the rasters agreed to within 17% with our photoelectric results. Taking this as a whole, the indication is that the errors in the calibrated rasters are not significantly larger than the errors in the original spectrophotometry itself.

Unfortunately, it is not possible to accurately assess errors in the surface brightness calibration across the field. Such errors could arise from wavelength independent variations in sensitivity across the face of the image tube. Vignetting and curvature of field of the tele-

scope and image tube are not corrected for absolutely, although errors in curvature of field are corrected for in a relative sense during the alignment procedure.

C. Comparison of the Methods of Direct Imagery and Spectrophotometry

Use of direct imagery for obtaining spectral data on an object involves trading the high resolution spectral data (generally of low spatial resolution) of spectrophotometry for high resolution spatial information (generally of much lower spectral resolution) over a large field. As discussed above, for strong emission lines, careful treatment of photographic images, with particular attention paid to the quality of the photographic characteristic curves used to convert photographic densities into incident intensities for different ranges of density, can yield results with comparable accuracy to photoelectric spectrophotometry. Better treatment of the problems of image tube thermal background and inhomogeneous sensitivity by use of flat field plates (to map the image tube sensitivity) and long dark exposures (to map the thermal background) could further improve the accuracy over that possible in this paper, for weak lines in particular.

There are a number of drawbacks with using calibrated direct photographic imagery for spectral studies. (1) It is necessary to preselect which emission lines are to be observed. This must be weighed against the fact that with spectrophotometry it is necessary to preselect spatial locations. (2) Photographic imagery is limited to lines which can be resolved from other nearby lines with available interference filters. This limitation probably prohibits use of this method for lines closer together than H α at a wavelength of 6563 Å and the [N II]

lines at 6584 Å and 6548 Å. This is a serious problem, because it prohibits obtaining information such as densities from the line pair of [O II] $\lambda\lambda$ 3726, 3729. (3) It is important for variations in radial velocity across the object observed to be small, since large radial velocity shifts could move the positions of lines enough to change the response of the filter, and result in velocity dependent surface brightness maps. This is especially important for lines such as H α and [N II] $\lambda\lambda$ 6548, 6584, where such shifts can also lead to spatial variations in contamination from neighboring lines. (4) Imagery provides no information about line shapes, which are useful in determining kinetic temperatures and velocity dispersions due to turbulence (cf., Shull et al., 1982).

The advantages of direct imagery over spectrophotometry stem from the dramatic increase in spatial information obtained. (1) Direct imagery removes difficulties in uncertain knowledge of slit placement present in spectrophotometric data, except insofar as spectrophotometry is used to calibrate the imagery data. (2) As discussed below, the low surface brightness areas between bright filaments are very interesting, particularly in light of the fact that changes in spectral line ratios do not follow the surface brightness structure as viewed in various lines. The preselection of bright filaments for spectrophotometric study by previous investigators (Miller, 1974; Fesen et al., 1982; etc.) has overlooked the importance of the more diffuse emission present in the remnant. (3) Due to their size, the slits used in spectrophotometry also integrate over the scale of much of the structure apparent in the data presented here. (4) Direct imagery allows quantitative analysis of spectral line ratios within the context of detailed spatial morphology.

Figure 9 shows surface brightness profiles taken along the slit of Miller's (1974) position 2 (S1 on Figs. 2 and 3) for [O III], H α , [O II], and [O I], and ratio profiles for [O III]/H α , [O II]/H α , and [O III]/[O I]. Along the slit, these ratios vary roughly by factors of 3, 2, and 6, respectively, indicating that a fairly wide range of physical conditions are present within the slit. Similarly, the wide variations in spectral line ratios present along the "spur" discussed in Sections III and IV indicate changing physical conditions along a single feature which has a size comparable to that of features chosen for study using spectrophotometry. This provides direct evidence for the idea (Benvenuti et al., 1979) that interpretation of spectrophotometry of filaments in SNR's is complicated by the presence within the slit of a number of shocks with different parameters.

Figure 9. Spatial surface brightness and line ratio profiles along Miller's (1974) position 2 (S1 on Figures 2 and 3). Arrows on Figures 2 and 3 indicate movement from left to right along the profiles. Each profile is accompanied by a label and two numbers. The lower number is the reference level for the profile at the large tick. The upper number is the interval for the profile represented by the separation between small ticks. The unit of surface brightness is 10^{-9} erg $\text{cm}^{-2} \text{s}^{-1} \text{str}^{-1}$. Numbers accompanying ratios give log values.

III. Data

In this section we present the data in a number of forms, but with little effort at interpretation except for discussion of line of sight superposition and geometrical effects. Particular attention is paid to certain line ratios such as $[O\ III]/[O\ II]$ because of their importance in comparing observational data with model calculations and their relevance to the problems encountered when attempting such comparisons. Because of the large amount of data presented here, we selected locations for detailed discussion largely on the basis of their apparent simplicity (the "spur" discussed in Section D) or because they appear to be representative of the behavior of a larger region (slices in Sections B and C).

A. Overall Appearance and Structure

It has been known for some time that the appearance of the Cygnus Loop and other SNR's changes markedly when viewed in the light of different emission lines (Chamberlain, 1953). However, previous treatment of interference filter plates have been only semi-quantitative at best. Parker (1973) stressed that in particular the appearance of the remnant in $[O\ III]$ differs significantly from other lines. Fesen et al. (1982) report similar findings. Specifically, the $[O\ III]$ structure tends to be more filamentary and arcuate than other lines, with $[O\ III]$ features sometimes seen on the leading edge of regions in which all lines appear.

Figures 4-7 show surface brightness and line ratio maps of the field studied. It is apparent that very complex spatial structure

exists in the surface brightness maps on scales ranging from the limit of resolution ($\sim 3''$) to the size of the field. The region is composed of arcs, filaments, knots, and larger scale features at all angles to each other. The general appearance changes markedly between [O III] and Balmer line emission. The morphology of [N II] and [S II] images are very similar to Balmer emission, with [O II] being intermediate in both its filamentary nature and spatial location between these lines and [O III]. The strength of [O I] features generally increases toward the inside of the Loop, with innermost features often present only in [O I]. The maps of the line ratios also show a complex structure — one that is both very different from, and in a sense more ordered than the surface brightness structure. Of particular interest here are the facts that (1) our maps show line ratios for the areas of faint emission between bright filaments, as well as for the filaments themselves, and (2) that the features which appear in the ratio maps are not the same as the features which are apparent in the surface brightness maps. The [O III]/H α and [O III]/[O II] maps are very similar, but the [O II]/H α map is not flat, and in fact weakly resembles the [O III]/H α map.

Figure 10 shows the log of the [O III]/H α ratio plotted against the log of the [O III]/[O II] ratio for "raster spectrophotometry" (as discussed above) of 16 locations from our field (designated on Figures 2 and 3), including bright knots apparent in surface brightness maps of different lines, "knots" apparent in maps of line ratios, and locations in low surface brightness areas between bright filaments. These results are tabulated in Table 5. Also plotted are photoelectric results for the Cygnus Loop from Miller (1974) and Fesen et al. (1982). With a few

Figure 10. Log-log plot of $[O\ III]/H\alpha$ vs. $[O\ III]/[O\ II]$ for "raster spectrophotometry" of 16 locations in our field. Plus signs (+) are prominent $[O\ III]$ surface brightness features, (@) are prominent $H\alpha$ surface brightness features, and (%) are locations of diffuse emission between surface brightness features. Also shown are photoelectric observations of Fesen et al. (1982) (#) and Miller (1974) (*).

Table 5
Results of "Raster Spectrophotometry"

Location	[O II]	H β	[O III]	[O I]	[N II]	H α	[S II]	Type
1	1412	100	392	39	189	245	168	Prominent [O III]
2	1623	100	787	69	262	315	210	Prominent [O III]
3	1593	100	1179	48	180	235	237	Prominent [O III]
4	1693	100	1032	69	235	279	171	Prominent [O III]
5	1185	100	340	87	243	294	450	Prominent [O III]
6	977	100	386	95	209	299	409	Prominent [O III]
7	965	100	99	70	182	274	497	Prominent H α
8	989	100	79	83	179	296	425	Prominent H α
9	475	100	33	218	222	329	485	Prominent H α
10	524	100	109	171	164	293	592	Prominent H α
11	949	100	123	90	207	283	591	Prominent H α
12	1132	100	487	35	139	241	245	Diffuse
13	1263	100	740	60	145	245	---	Diffuse
14	1145	100	376	38	161	248	200	Diffuse
15	785	100	129	122	193	297	229	Diffuse
16	785	100	100	96	154	255	361	Diffuse

exceptions, our "knots" cover the same region on this plot (and all others like it) as those from the previous authors' spectrophotometry. Whatever the interpretation of these line ratios, the fact that our data cover the same region in these plots as previous spectrophotometry does indicate that the range of physical conditions in the field we observed represents most of the physical conditions found for the entire Cygnus Loop. This agreement also confirms our calibrations in a statistical sense.

In Figure 11 we plot the values of the log of each potentially interesting line ratio against the value of the log of the $[O\ III]/[O\ II]$ ratio for each pixel in the field. On these plots a pixel is not plotted unless all four lines used in the plot have values above their respective floors, as discussed above. Also plotted in Figure 11 are model calculations from Raymond (1979) and Shull and McKee (1979). In Section IV these models will be described and their correlation with the data will be discussed. Table 6 gives a brief list of the parameters of these models.

The abscissa of these plots was chosen to be the $[O\ III]/[O\ II]$ ratio in part because it has the least number of pixels systematically excluded by the suppression of very low value pixels. Other reasons for the choice of the $[O\ III]/[O\ II]$ ratio are that since both lines are very strong over most of the field, the signal to noise in the ratio is good, and that the ratio changes by a factor of ~ 50 in the field. There are also two theoretical reasons for being interested in this ratio. (1) According to model calculations it is very sensitive to shock velocity. In surveying correlations between other combinations of line ratios, no strong correlations other than those relating ratios

Figure 11a. Pixel by pixel log-log plots for the entire field of all potentially interesting line ratios vs $[O\ III]/[O\ II]$. Pixels for which one or more contributing lines are below their floors are not plotted. No effort is made to show density contours of the points. Also shown are velocity sequences of models from Raymond (1979) (capital letters) and Shull and McKee (1979) (lower case letters) (see Table 6 for parameters).

Figure 11b.

Table 6
Shock Model Parameters*

Raymond (1979) Model	v_s (km s ⁻¹)	Shull & McKee (1979) Model†	v_s (km s ⁻¹)
A	50	a	40
B	60	b	60
C	70.7	c	80
D	81.5	d	90
E	100	e	100
F	120	f	110
G	141	g	130
H	160		
I	200		

*All models have $n_0 = 10 \text{ cm}^{-3}$, $B_0 = 1 \text{ } \mu\text{G}$, "cosmic" abundances.

†Lower case letters are used for consistency with Fig. 11 and 18.

predicted to be velocity sensitive were found. (2) This ratio should also be less sensitive to possible effects of non-steady flow than other [O III] ratios (since [O II] should be produced closer to [O III] in the recombination region behind the shock than are other lines).

From Figure 11, a number of remarks can be made about the correlations between line ratios. (1) The log of the ratios of [O III]/[N II] and [O III]/H α are linearly correlated with the log of the [O III]/[O II] ratio. (2) While the range in the [O III]/[S II] and [O III]/[O I] ratios is still large, the correlations of the log of the [O III]/[O II] ratio with the logs of the [O III]/[S II] and [O III]/[O I] ratios are not as tight as with the logs of the [O III]/H α and [O III]/[N II] ratios. (3) Ratios of [O II] with [N II], [S II], and H α also show systematic variations with [O III]/[O II], with the changes in these ratios across the range of values of [O III]/[O II] comparable to the scatter in their values for a single value of [O III]/[O II]. (4) Correlations involving [O I] are in general not as tight as most other observed correlations. (5) Ratios between [N II], [S II], and H α tend to be very flat. In particular, [N II]/H α has a value of $.67 \pm .25$ over a spread of [O III]/[O II] values of a factor of > 30 . Table 7 gives fits to the equation $\log (\text{line 1/line 2}) = A + B \log ([\text{O III}]/[\text{O II}])$ for these ratios, along with correlation coefficients and σ^2 for the fits. This helps to quantify the qualitative discussion above, and should facilitate future comparisons of the Cygnus Loop with other SNR's.

Table 7

Empirical Fit to $\log(\text{Ratio}) = A + B \log([\text{O III}]/[\text{O II}])$

Ratio	A	B	r^2	$\sigma^2 (\times 10^2)$
$[\text{O III}]/\text{H}\alpha$	0.68	1.17	.86	1.37
$[\text{O III}]/[\text{N II}]$	0.89	1.25	.88	1.20
$[\text{O III}]/[\text{S II}]$	0.71	1.29	.76	3.07
$[\text{O III}]/[\text{O I}]$	1.07	0.98	.41	7.07
$[\text{O II}]/\text{H}\alpha$	0.68	0.17	.12	1.37
$[\text{O II}]/[\text{N II}]$	0.89	0.25	.23	1.20
$[\text{O II}]/[\text{S II}]$	0.71	0.29	.14	3.07
$[\text{O II}]/[\text{O I}]$	1.07	-0.02	.00	7.07
$[\text{N II}]/\text{H}\alpha$	-0.19	-0.04	.02	0.34
$[\text{N II}]/[\text{S II}]$	-0.16	0.06	.01	1.64
$[\text{N II}]/[\text{O I}]$	0.32	-0.10	.02	3.27
$[\text{S II}]/\text{H}\alpha$	-0.02	-0.09	.04	1.21
$[\text{S II}]/[\text{O I}]$	0.48	-0.18	.05	3.06
$[\text{O I}]/\text{H}\alpha$	-0.50	0.08	.01	2.63

B. Structure and Morphology of Selected Regions

Figure 12 shows the field studied divided, for purposes of discussion, into four regions on the basis of general morphological characteristics. The following subsections deal with these regions one at a time.

(1) Region I

Region I is a broad (.2-.5 pc wide) band stretching from the top left to the lower central portion of the field. This region is characterized by numerous arcs and knots embedded in weaker and more diffuse emission, and is at least partially visible in all emission lines observed. The variation of the structure as viewed in different lines is similar to that in other portions of the loop discussed by other authors (Parker, 1967; Fesen et al., 1982). The [O III] structure is in general the most filamentary, and begins "ahead" of features visible in lines of other ions. However, there is also a diffuse component of the [O III] emission present, as well as a region of "overlap" where features are visible in all lines. The [O I] structure is the most diffuse, and continues further "behind." The behavior of the other lines is intermediate between these two extremes with regard to both filamentary appearance and position, with [O II] most resembling [O III]. The [O III] ratio maps (Figures 6 and 7) show this effect most clearly. There is a well defined leading edge of high [O III]/X, behind which these ratios decline in a way that is largely independent of the spatial structure apparent in the surface brightness maps. The direction of the gradient of the [O III]/X ratios is roughly perpendicular to the radial direction for the horizontal bar. This gradient indicates that the E-W bar near

Figure 12. Schematic drawing of the field divided into Regions I-IV for discussion in Sections III and IV.

the center of the field is the result of a part of the blast wave moving non-radially (from the geometrical center of the SNR), rather than a foreground or background feature which is in some way wrapped around.

Figure 13 shows surface brightness and line ratio profiles along a 193" long "slice" through the northeastern part of Region I at S2 (see Figures 2 and 3) perpendicular to the apparent edge of the structure, and parallel to the gradient in the $[O\ III]/[O\ II]$ ratio. There are four strong features present in $[O\ III]$ (marked by arrows on the figure) located at 20", 43", 62", and 125" along the slice, and a weaker $[O\ III]$ feature present at 170". For the first 100 arcseconds of the slice, the structure as viewed in all lines is very similar. With the exceptions of the feature at 20" (which is weak in all lines except $[O\ III]$ and (somewhat suprisingly) $[S\ II]$, and is absent in $[O\ I]$) and the $[O\ I]$ feature at 90" (which is absent in all other lines), all features are present in all lines. Along this interval, the $[O\ III]/H\alpha$ and $[O\ III]/[O\ II]$ ratios decline smoothly, showing none of the features present in the surface brightness profiles. The $[O\ III]/H\alpha$ ratio drops monotonically across all four of the features present in the surface brightness profiles, falling from a value of ~ 3 to ~ 0.8 . The $[O\ III]/[O\ II]$ ratio similarly declines from ~ 0.8 to ~ 0.2 . The $[O\ II]/H\alpha$ ratio varies from 3.4 to 5.9, and the peaks and valleys are also independent of the surface brightness structure.

Beginning around 100", the structure of $[O\ III]$ becomes different from the other lines. There is a wide $[O\ III]$ feature which peaks at 125" which is only weakly present in the other lines. There are also two features at 150" and 175" which are present in all lines except $[O\ III]$. The feature at 175" is particularly strong in $[O\ I]$. In

Figure 13. Spatial profiles as in Figure 9 for 193'' slice at S2 (see Figures 2 and 3). Arrows indicate features discussed in the text.

the $[O\ III]/H\alpha$ and $[O\ III]/[O\ II]$ ratio profiles there is a broad ($\sim 35''$ wide) feature beginning at about $105''$ along the slice. This feature encompasses the $[O\ III]$ feature at $125''$, and terminates at the surface brightness feature present in the lines of lower ionization species at $150''$. For the feature beginning at $105''$, the $[O\ III]/H\alpha$ and $[O\ III]/[O\ II]$ ratios rise to values comparable to their values at the beginning of the slice, remain relatively constant for $30''$, then drop to values of 0.5 and 0.1, respectively. There is also a broad but less well defined feature in the $[O\ II]/H\alpha$ ratio at this location. This location was found to be one of the few significant exceptions to the trend evident at essentially all other locations studied that once surface brightness features become present in an emission line, the ratio of $[O\ III]$ to that line generally decreases behind the leading edge of the region independently of surface brightness structure.

There is a $20''$ wide sinusoidal variation with an amplitude of about 0.2 dex in the log of the $[O\ III]/H\alpha$ and $[O\ III]/[O\ II]$ ratios across the $[O\ III]$ feature at $170''$ and the feature at $175''$ present in all other lines. The sinusoidal character of the ratios is due to the slight difference in position of the $170''$ and $175''$ features. The $[O\ II]/H\alpha$ ratio is flat across here. While the features at $170''$ in $[O\ III]$ and $175''$ in the other lines might appear to be the "same feature" with a slightly different position when viewed in different lines, we find no direct evidence for this. From the first three features along the slice (and many other features present in the data), it appears that if a feature is present in any two or more lines, then its location as viewed in each of those lines is the same. We also find in general that whenever a series of surface brightness features is present in two lines, then the

ratio of those two lines is independent of the surface brightness structure. A plausible explanation for the type of behavior seen in the last 90" of the slice at S2 involves a line of sight superposition of features with strong [O III] (and moderate [O II]) on top of features which are present primarily in lines of lower ionization states.

Figure 14 shows profiles at S3 across the horizontal bar in Region I. Four features are apparent in [O III], located at ~35", ~45", ~65", and ~80" along the slice. The feature at 65" is very weak. The last three of these features also appear in [O II], H α , [N II], and [S II]. Only the last feature at 80" appears unambiguously in [O I], although there is also some suggestion of the feature at 65". The additional feature at 21" which appears only in [S II] is apparently an artifact of the suppression of very low data values during coadding.

There is some suggestion of the presence of the feature at 35" in [O II]. The feature at 45" is very pronounced in [O III] and [O II]. It is less pronounced in H α , [N II], and [S II] relative to the feature at 80". The [O III]/[O II] ratio jumps to a value > 1 at the location of the [O III] feature at 35", then declines steadily from there, again independently of the surface brightness structure, until the position of the 80" feature, where there is a sinusoidal variation in the log of the ratio of amplitude $\sim .1-.15$ dex, superimposed on the general decline. The [O III]/H α ratio behaves in a similar way, except that the ratio has two peaks corresponding to the [O III] surface brightness features at 35" and 45". The ratio goes to ~ 6 in these locations, then declines fairly smoothly along the rest of the slice to a value of $\sim .4$. The [O II]/H α ratio jumps by a factor of about 1.4 at the location of

Figure 14. Spatial profiles as in Figures 9 and 13 along S3. Gaps in ratios are due to data below floor for generation of reliable ratios.

the second intensity peak, then also becomes independent of the intensity structure, declining slightly from a value of 5.5 to a value of 3.5.

These two slices, as can be seen by examination of the surface brightness maps (Figures 4 and 5) and color coded line ratio maps (Figures 6 and 7), are indicative of the type of structure found generally throughout Region I. Moving back through the region along a line perpendicular to its edge, [O III] surface brightness features are encountered first. Further back, features visible in the other observed lines are encountered, roughly in the inverse order of the ionization potential of the ionic species responsible for the line. From Figures 13 and 14 it is also apparent that the relative strength of trailing features as viewed in [O I] increases. In [O III] these features are weaker, and sometimes completely absent. This behavior can be confirmed in general by examination of the surface brightness maps. The scale for establishment of [O I] features once [O III] features are present is 20 to 40 arcseconds (see figures discussed above). In addition, features found in [O II] sometimes precede features also found in $H\alpha$ by a few arcseconds. (This does not necessarily imply the existence of an extraordinarily extended recombination region, but only that the character of the emission changes in some systematic fashion with distance behind the blast wave.)

Line ratios for two lines show features coincident with surface brightness features when the surface brightness features are well established in only one of the lines. For example, the [O III] feature at 35" along S3 (Figure 14) is not present in [O II] or $H\alpha$, and both the [O III]/ $H\alpha$ and [O III]/[O II] ratios show peaks at this location.

The feature at 45" is well established in [O II], but is not strong in H α , and the [O III]/H α and [O II]/H α ratios show peaks at this location. Once surface brightness features become well established in two lines, however, the behavior of their ratio becomes largely independent of the surface brightness behavior of the two lines. For example, the [O III]/[O II] ratio declines smoothly across the surface brightness feature at 45" along S3. The independence of the behavior of line ratios from surface brightness features can also be seen from the slice along S2 (Figure 13). These two slices also show the smooth declines of [O III]/X ratios with increasing distance behind the leading edge of Region I. The independence of line ratios and surface brightness features and the presence of smooth trends in line ratios spanning a number of surface brightness features are interesting facts — facts that have not been appreciated before, due to the inability of spectrophotometry to accurately examine line strengths between bright filaments. Hereafter, we will refer to the pattern of all surface brightness features present in all (or almost all) lines, with line ratios independent of the surface brightness structure, as "Type I" behavior.

(ii) Region II

Region II is actually composed of two regions, each consisting primarily of well defined arcs seen primarily in [O III]. The strongest feature of this sort is the arc south of the southeast corner of Region I. This arc is very pronounced on the [O III] surface brightness map, weakly present on the [O II] map, and essentially absent on all other surface brightness maps (Figures 4 and 5). Figure 15 shows profiles along a slice at S4 through the bright knot near the center of this

Figure 15. Similar profiles for slice at S4.

arc. This knot is located at the intersection of the bright vertical arc, and a weaker arc running primarily east-west. There is a single pronounced feature in [O III] located at 45" along the slice. This feature is also weakly present in [O II]. Features such as this arc which appear almost exclusively in [O III] (and perhaps weakly in [O II]) we will refer to hereafter as "Type II" features. The structure of the [O II]/H α ratio (and to a lesser extent the [O III]/[O II] ratio) is correlated with [O III] surface brightness structure for Type II features. The [O III]/H α and [O III]/[O II] ratios have their maximum values of ~ 8 and 1.8 at the leading edge of this feature, then decline behind it. Both of these ratios likely go higher, but the lack of strong H α and [O II] at the very leading edge of the arc prohibit the generation of good ratios (and so they show up as grey on the color coded [O III]/[O II] and [O III]/H α ratio maps of Figure 6 and 7). This arc also seems to be physically associated with, or at least physically similar to, the region immediately south of it. This can be seen by looking at the [O III] ratio maps. At a location just south of the border of our field, the [O III]/H β ratio reaches a value of 45 (Fesen, private communication).

Figure 16 shows profiles along S5, through the intersection of Region I and the Type II [O III] arc seen at 45" along S4. This slice shows Type I behavior, with features (at 55", 70", and 84") present in all lines, with the exception of the very strong [O III] feature at 36". This feature corresponds to the top of the Type II arc. The [O III]/H α ratio has a sharp peak at this location. Moving away from the feature at 36", the [O III]/H α ratio drops suddenly by a factor of 2.7 from a value of ~ 9 to ~ 3.3 . The [O III]/[O II] ratio behaves

Figure 16. Similar profiles for slice at S5.

similarly, declining suddenly by a factor of 2.2 from a value of ~ 1.4 to 0.65. The $[0\ II]/H\alpha$ ratio, which is fairly constant at a value of ~ 5 for most of the slice, rises to ~ 7.5 here. This is just the behavior expected for a linear superposition of a feature with an excess of $[0\ III]$ and $[0\ II]$ (such as a Type II feature or a feature such as those found along the leading edge of Region I) and a "well behaved" Type I structure. This behavior is also very similar to that observed at the two positions of high $[0\ III]/H\alpha$ located behind the leading edge of Region I, suggesting that these might also be line of sight superpositions of Type I structures and features which are strong in $[0\ III]$ and present in $[0\ II]$.

From these and other data studied, it can be said fairly generally that the highest values of the ratios of $[0\ III]$ with other lines such as $H\alpha$ and $[0\ II]$ are found along the leading edges of structures where there is a prominent surface brightness feature which is present in $[0\ III]$, but which is absent in other lines (Type II behavior). Occasionally, high $[0\ III]/X$ ratios are found behind the leading edges of structures. We believe that such instances are due to line of sight superpositions of Type I and Type II features. Such superpositions would result naturally from the projection onto the plane of the sky of the roughly spherical geometry of the SNR.

Type I and Type II features represent extremes of a continuous range of behavior. For example, the 45" feature in Figure 15 is strong in $[0\ III]$, moderately strong in $[0\ II]$, and weak or absent in all other lines. The $[0\ III]/[0\ II]$ ratio declines smoothly across this feature, exhibiting Type I behavior. On the other hand, since the feature is not strong in $H\alpha$, the $[0\ III]/H\alpha$ ratio has a peak at this location, as is

found with Type II features. There is a peak in the $[O\ II]/H\alpha$ ratio at this point, which is also characteristic of this type of feature. We hereafter refer to such intermediate behavior as "Type I.5".

Another example of Type II features is located in the north central part of the field (the second area marked Region II on Figure 12). Here there are a number of $[O\ III]$ arcs, embedded in a diffuse background of other lines. These arcs are again weakly present in $[O\ II]$, and can be seen on the $[O\ II]/H\alpha$ map. In light of the general notions about the filamentary behavior of $[O\ III]$ discussed here and by other authors, (Parker, 1967; Fesen et al., 1982), it is interesting to note that at this location, the $[O\ III]$ filaments serve as an envelope for diffuse $[O\ III]$ emission.

(iii) Region III

Region III is the vicinity of Miller's (1974) position 2. It consists of an area of very high surface brightness in all observed emission lines, with a linear "spur" extending from this area for a distance of about 2 arcminutes to the southeast. The highest surface brightness part of the region is around Miller's position 2 and has a very complex structure as viewed in all lines. $[O\ III]$ in particular shows many separately traceable filaments which intersect to form bright knots. At this location the difference in the structure as viewed in surface brightnesses of various lines and the structure as viewed in line ratios is particularly evident (see Figures 6 and 7). For example, the ratio maps show the "spur" to be a continuous feature that hooks into the region of Miller's slit. On the surface brightness maps, the feature gets lost in the bright region surrounding Miller's slit. The

discrepancy in position between bright [O III] knots and H α knots is shown by Shull et al., (1982). The strong "knot" of high [O III]/H α and [O III]/[O II] located at (415,180) (using the field coordinates defined in Section II) is due to the ratio of moderately strong but non-filamentary diffuse [O III] emission with fairly weak H α and [O II] emission. The "knot" of low [O III]/H α and [O III]/[O II] at (425,160) is likewise due to not so much to the presence of a strong H α knot, as it is the absence of strong [O III]. This is another example of the common lack of detailed correlation between surface brightness features and knots and other structures in the line ratio maps which is observed throughout the field studied.

The linear "spur" in this region is a very interesting feature. Slices taken perpendicular to the "spur" at several locations along its length show that it is well established in surface brightness for all lines along its entire length, with the location of the center of the feature as viewed in all lines agreeing to within a pixel. It is also a "clean" feature, which is clearly physically related along its length, and has very little apparent contamination from other background or foreground features. Figure 17 shows a slice taken along S6 down the center of the "spur." The [O III] surface brightness along the "spur" stays relatively constant, while the surface brightness of all other lines drops off approximately exponentially along its length. The [O III]/H α and [O III]/[O II] ratios increase along the first 80" of the slice from values of .7 and .1 to values of 3.5 and .7, respectively. These upper values then remain approximately constant for the last 20" of the "spur".

Figure 16. Similar profiles for slice along the center of the "spur" at S6.

Plots of the logs of line ratios versus $\log ([O\ III]/[O\ II])$ for a seven pixel wide strip centered along the ridge of the "spur" are shown in Figure 18. Also shown are model calculations as discussed for Figure 11. The $[O\ III]/[N\ II]$ and $[O\ III]/H\alpha$ ratios are correlated with $[O\ III]/[O\ II]$ for this region in the same way as they are for the entire field, except for the lack of the very high $[O\ III]$ ratios present elsewhere in the field. The correlation is also a bit tighter for this smaller region. There is a top end to these ratios, where they level off for the southeast end of the "spur." This shows up as a bunching of points at the high $[O\ III]$ end of these plots. All other ratios also show correlations which are much tighter than correlations for the entire field, but these deviate from the simple linear relations discussed before. In particular, all of the ratios show some kind of "turnover" or "hook" at an $[O\ III]/[O\ II]$ ratio of about 0.5. The amount of scatter in the correlations for the entire field seems related to the degree of the turnover in the correlations for the "spur." The lines with the worst correlations overall show the strongest turnovers in the strip along the "spur" at this critical value of $[O\ III]/[O\ II]$. Some line ratios, such as $[N\ II]/[O\ I]$, show overall behaviors which are different than those for the field as a whole, even for smaller values of $[O\ III]/[O\ II]$. $[N\ II]/H\alpha$ also shows a definite decline by a factor of about 1.8, with a factor of 1.15 scatter in the correlation.

(iv) Region IV

This region is located near the western edge of the field, and includes the position of the new spectrophotometry used to calibrate the

Figure 18a. Same as Figure 11 for a 7 pixel wide strip along the "spur".

Figure 18b.

[O I] raster. It is characterized by bright emission from the low excitation lines, especially [O I]. The dimensions of the brightest part of this region are about 30" x 45", which are somewhat larger than most "knots". The surface brightness of [O III] emission is extremely weak in this region, while the structure is present but not pronounced in [O II]. The [O II]/H α ratio drops to a value of 1.4 here, while the [O I]/H α ratio rises to a value of 0.7. The [O III] surface brightness is too weak for generation of good point to point line ratios, but our photoelectric spectrophotometry and "raster spectrophotometry" indicate that the [O III]/H α ratio is less than .15 at this location. It should also be noted that the fact that the [O III] surface brightness is below the floor set for generation of reliable pixel by pixel ratios causes this region to be systematically excluded from the line ratio correlation plots shown in Figure 11. There is also a suggestion of a slight enhancement of the H α /H β ratio at this point, although this is a 1 σ effect, and could also be due to the previously discussed difficulties in image tube background, which are worse in this region.

IV. Discussion

A. General Model Comparisons

When attempting to compare model calculations of shocks with actual observation, one immediately encounters the problem of which of the many free parameters available in the models should be varied to match a given observation. This also poses the problem that even if a reasonably close match is obtained, there is no guarantee that it is in any sense unique. For example, Raymond (1979) concluded that depleted abundances are suggested by Miller's spectrophotometry of the Cygnus Loop, but later (Raymond, 1981) found this not to be the case. We do not try to make detailed comparisons between line strengths at particular locations and specific model calculations. Rather, (in the context of the spatial structure apparent in the surface brightness and line ratio maps, and the assumption that the data represents some fairly continuous range of physical conditions) we look at variations in line ratios in the profiles and log-log plots to see if there is qualitative agreement between the behavior of the observations and the behavior of models with parameters which are plausible for the field observed.

Spectral properties of shocks are functions of a large number of parameters, including such quantities as preshock ionization, density variations in the preshock medium, magnetic field strength, and lateral extent of the shock front. However, assuming that elemental abundances are reasonably uniform across the field observed, there are only two mechanisms likely to be significant in determining the observed systematic variations in spectral characteristics across the field. The first of these is spatial variations in shock velocity. Assuming that

complete recombination regions are present, lines such as [O III] are very sensitive to variations in the velocity the shock over a significant range of velocities (Cox, 1972; Raymond, 1979). A second potentially significant issue is the presence of incomplete recombination regions, or "non-steady flow" (Raymond, 1981; Fesen et al., 1982). With this in mind, our primary emphasis in the discussion is two fold. First, we compare the systematics of the observed variations in line ratios with model calculations covering a wide range of shock velocities. Second, we discuss the implications of the observed spatial structure of the remnant on the issue of where the assumption of steady flow is valid.

Figure 11 shows log-log plots of the correlations between all potentially interesting line ratios and the [O III]/[O II] ratio for the entire field. Also shown are the calculations of Raymond (1979) for a series of shocks with similar preshock conditions, but shock velocities ranging from 50 km/sec to 200 km/sec, and a similar set of models from Shull and McKee (1979) for shocks with velocities from 40 km/sec to 130 km/sec. The primary difference between these two sets of models is that those of Shull and McKee have a self consistent treatment of the UV precursor of the shock and the ionization of the preshock medium. Since it is neither likely that the only source of ionization of the preshock gas is the radiative precursor of the shock, nor likely that Raymond's guesses for the ionization state of the preshock gas are universally applicable, these two sets of models provide a handle on the uncertainty in models due to preshock ionization. Interestingly, the loci of the two sets of model calculations have roughly the same slopes on the log-log plots for the lower velocity shocks (at least for the [O III]

ratios), but differ from each other by a relatively constant factor. Neither of these sets of models treat charge exchange adequately, although Shull and McKee treat this process more thoroughly than does Raymond. Inclusion of charge exchange has the general effect of decreasing the degree of ionization at any given location in the recombination region (Butler and Raymond, 1980). For their 120 km/sec model, the $[O\ III]/H\beta$ ratio is reduced by the inclusion of charge exchange, while the $[O\ II]/H\beta$ ratio is enhanced by the reactions which favor singly to doubly ionized oxygen. For slower shocks, $[O\ II]$ is weakened with respect to other lines. For Butler and Raymond's 60 km/sec model, inclusion of charge exchange reduces the $[O\ II]/H\beta$ ratio by a factor of 3.25.

On the log-log plots shown in Figure 11, the correlations between all line ratios and the $[O\ III]/[O\ II]$ ratio agree reasonably well with the model calculations for shocks with velocities $\lesssim 100$ km/s for $n_0 = 10\text{ cm}^{-3}$, $B_0 = 1\text{ }\mu\text{G}$, and "cosmic" abundances. The slopes of the loci of points for the $[O\ III]$ ratios are somewhat greater for the observational data than for the model calculations. While charge exchange in astrophysical shocks is not completely understood, and is itself a strong function of density, its effects at least qualitatively help account for the discrepancies in slopes of $[O\ III]$ ratios on the log-log plots. Butler and Raymond's calculations show that inclusion of charge exchange in shock models weakens $[O\ III]$ in slower shocks relative to its strength in faster shocks. The relative strength of $[O\ II]$ between slow and fast shocks is affected in the same sense, but to a lesser degree than $[O\ III]$. The relative strengths of the other observed lines between the 60km/sec and 120 km/sec models are not significantly affected

by charge exchange. As a result, the behavior of the $[O\ III]/[O\ II]$ ratio will be less affected by charge exchange than the ratios of $[O\ III]$ with the lines of the other ions. This should increase the slopes of the loci of model calculations between these other ratios and $[O\ III]/[O\ II]$ when plotted on a log-log diagram. The resulting effect of charge exchange on the slopes of the loci of model calculations for $[O\ III]$ ratios as plotted in Figure 11 should be in the proper sense and of roughly the proper magnitude to account for the discrepancies observed between our data and the model calculations done without adequately treating charge exchange. A set of models including charge exchange needs to be run for a sequence of shock velocities to verify this in detail.

The observational correlations of all other line ratios with the $[O\ III]/[O\ II]$ ratio are in similar agreement with steady-flow model calculations. As with the $[O\ III]$ ratios, the slopes of the loci of observational points for the ratios of $[O\ II]$ with the lines of other ions differ from the models in the sense suggested by the inadequate treatment of charge exchange in the models plotted. The ratios of lines not affected significantly by charge exchange agree very well with the predictions of these models.

The width of the correlations of the observational data is comparable to the discrepancy between the two model sets shown. The scatter is widest for the $[O\ I]$ ratios in general, and for the $[O\ II]/[O\ I]$ ratio in particular. This is likely in part due to the relatively poorer quality of the $[O\ I]$ plate. However, the $[O\ I]$ ratios are also predicted to turn over sharply for shocks in excess of ~ 100 km/sec. Line of sight superposition of a shock lying on the horizontal portion of the

relationship predicted by models (as plotted in Figure 11) and a shock lying on the vertical portion of the predicted relationship would fall in the space between the two portions on these plots, producing just the sort of scatter seen. The locus of pixels plotted shows a fairly well defined upper boundary, which is also consistent with such a scheme. The strong enhancement of [O I] by the inclusion of charge exchange (a factor of 2.09 for Butler and Raymond's 60 km/sec model and a factor of 2.14 for their 120 km/sec model) is also of the right order to bring the magnitude of the [O I] ratios in the model calculations into better agreement with the observational data.

These comparisons could be complicated by possible systematic relations between shock velocity and other shock parameters such as preshock density, and by possible differences in the spectral signature produced by variations in shock velocity when other parameters differ from the "standards" used in the models plotted in this paper. Due to the unavailability of extensive model grids covering variations in several shock parameters, we do not explicitly discuss such effects. However, the models which are available generally indicate that the trends in the velocity sequences presented here should be representative (Raymond, 1979).

It should be noted that the data we present here are not inconsistent with that of Fesen et al. This can be seen from Figure 10 where the results of their photoelectric spectrophotometry are plotted along with our "raster spectrophotometry". However, they draw very different conclusions than do we regarding the agreement between predicted line ratio correlations and observations. In large part this is due to the straight ratio versus ratio format in which they present their data.

Their figures emphasize the expected behavior of shocks with velocities greater than 100 km/sec and exaggerate the differences between observations and models with velocities less than or equal to 100 km/sec. By adopting a log-log format, on the other hand, we are able to demonstrate the basic similarity in the theoretical and observed correlations between line ratios, while more clearly identifying the nature of the discrepancies in functional form which do remain. A log-log format is also less sensitive to the introduction of "renormalization" of line ratios due to various effects (e.g., abundances which are different than the set used for the model calculations).

A serious problem remaining in attempting to match the behavior of line ratios with model predictions is the presence of [O III] ratios which are larger than can be easily accounted for. This problem has led other authors to the concept of "non-steady flow" (Raymond, et al., 1980; Fesen, et al., 1982). Basically, this idea states that under certain conditions only a portion of the recombination region will be present, and that the emission will be characteristic of partial recombination regions rather than of the integration over entire steady flow recombination regions found in published shock model calculations. Fesen et al. (1982) suggest that if the scale of the shocked clouds is small enough, the majority of emission seen may be due to incomplete recombination regions in different stages of cooling. If our interpretation is correct, however, non-steady flow is only needed to explain the high [O III] ratios. Here, the leading part of the recombination region (the source of the [O III] emission) is seen as being present before the rest of the recombination region has had a chance to form.

Roughly, this seems to correspond to values of $[O\ III]/[O\ II]$ greater than ~ 0.8 .

Observationally, locations with excessively large $[O\ III]$ ratios have a number of characteristics in common. They tend to be found along the leading edge of regions of emission, such as Region I, or in places where $[O\ III]$ arcs are present in the absence of corresponding features in lines of other ions. In both cases, excessively large $[O\ III]$ ratios are associated with Type I.5 or Type II features. They also coincide with locations where $[O\ I]$ is very weak. This is apparent from the suppression of pixels with high $[O\ III]/[O\ II]$ ratios on the log-log plots (Figure 11) for ratios involving $[O\ I]$. This suppression is due to the fact that for these pixels $[O\ I]$ is below its assigned floor for generation of good pixel to pixel ratios.

Type I.5 and Type II behavior is a very plausible signature for non-steady flow conditions. It is to be expected that the most recently shocked material would be found further ahead, and that the detailed surface brightness structure of $[O\ III]$ would be very different from that of $[O\ I]$ and other lower excitation lines at locations of non-steady flow, with $[O\ I]$ being largely absent. This would provide an observational criterion for testing the validity of the assumption of steady flow. If a surface brightness feature is established in emission lines from all observed ions (Type I behavior, e.g., features along S2 at 43" and 62", and S5 at 55", 70", and 84") then enough of a recombination region is present at that location to justify the assumption of steady flow. In particular, it is certainly arguable that if a feature is present in both $[O\ III]$ and $[O\ I]$, then the recombination region is at least well established through the regions responsible for lines of

[N II], [S II], [O II], and Balmer emission. Features present only in lines from low ionization potential ionic species could be reasonably explained by slower shocks which produce no [O III].

The presence of features which are visible in lines from portions of recombination regions with temperatures ranging from $\lesssim 10^5$ °K to $\sim 2 \times 10^3$ °K also supports the conclusion (Raymond et al., 1980) that thermal instabilities (e.g., McCray et al., 1975) are not a dominant process in determining the structure of the remnant. The question of whether the cloudlets present are large enough to contain entire recombination regions will be discussed below.

B. The "Spur"

Surface brightness and line ratio maps all suggest that the "spur" in Region III is both physically continuous along its length and discrete. This conclusion is supported by the fact that the relations between line ratios for this feature (Figure 18) are much tighter than the corresponding relations for the entire field. Values for the [O III]/[O II] ratio range from $\sim .1$ to $\sim .8$, increasing fairly smoothly from the northwest to the southeast along the length of the "spur" (Figure 17), indicating that physical conditions change significantly along the length of the feature. Further, the "spur" meets the criterion suggested above for validity of the assumption of steady flow along its entire length, since it is established as a surface brightness feature in all observed lines. Specifically, it is present in both [O III] and [O I], which strongly indicates that the assumption of steady flow is valid here.

The comparison of the observed relationships between different line ratios and model calculations are even better for this small region than for the field as a whole. The scatter in the locus of observational points is smaller for all line ratios, as would be expected for a situation in which preshock conditions vary smoothly along the "spur". For values of $[O\ III]/[O\ II] < 0.5$, the slopes of the loci of points on log-log plots for this small sample are very similar to those for the field as a whole. As such, the above discussion of the entire field regarding the agreement between our observations and model calculations with $v \lesssim 100$ km/sec apply to this smaller set of points as well. The peak $[O\ III]/[O\ II]$ ratio of ~ 0.8 , however, is in contrast to the very high $[O\ III]/[O\ II]$ values found elsewhere in the field (associated with Type I.5 and Type II features). There is a change of slope on the plots of all line ratios beginning when $[O\ III]/[O\ II]$ reaches a value of $\sim .5$ (which is not clearly seen on the log-log plots for the entire field) which matches well the critical behavior predicted by shock models for shocks $\gtrsim 100$ km/sec. This predicted behavior is due to the fact that not much additional $[O\ III]$ is being produced by shocks faster than ~ 100 km/sec. The only strong exception to the agreement between model calculations and observations at this critical point is that the $[S\ II]/[O\ I]$ ratio "hooks" the wrong way. Examination of the other $[O\ I]$ ratios in Figure 18 (particularly the $[O\ I]/H\alpha$ ratio) shows that this is due to the fact that $[O\ I]$ does not increase as dramatically as expected at this point.

The general agreement between model calculations and observations (specifically the presence of a predicted change in slope at an $[O\ III]/[O\ II]$ ratio of 0.5-0.8) lends further credence to the argument

that the assumption of steady flow is valid at this location. We find relationships between lines from ions found throughout a complete recombination region which are consistent with model predictions for a steady flow shock. This agreement would not be expected from looking at disjointed pieces of recombination regions (i.e., non-steady flow). Comparing the data with the plotted models indicates that the shock velocities along the "spur" vary from around 70 km/sec at its northwest end to ~ 120 km/sec at its southeast end. A detailed fit between models and observations should be possible for this feature because of the fact that it is "clean", and because the predicted critical behavior occurring at a shock velocity of around 100 km/sec is actually observed. No such detailed comparison is attempted here because of the lack of models which both adequately treat charge exchange and cover the range of parameters (notably a density and velocity grid) appropriate for this region. UV observations of this feature at several locations could be useful in confirming our steady flow interpretation and would allow a better determination of the range of shock velocities present.

A change in shock velocity along a feature such as this could be caused by an encounter between the blast wave with constant $n_0 v^2$ and an ambient ISM with a gradient in density perpendicular to the direction of propagation of the shock. Such a picture, amounting to large scale refraction of the shock, would require that n_0 change fairly smoothly by a factor of ~ 3 over a distance of $\sim .4$ pc. This type of interaction could also explain the fact that the "spur" is inclined at an angle to the radial direction. At the southeast end of the "spur" the shock is encountering less dense material, and is moving ahead faster than the shock at the northwest end of the "spur."

C. Types I and I.5 - Gradients in [O III] Ratios and Scales for Establishment of Steady Flow

As noted previously, with a few exceptions (which we attribute to geometrical effects), Region I is characterized by a leading edge of Type I.5 and Type II features which are strong in [O III], but relatively weak or absent in other lines. In particular, the leading features in Region I tend to be absent in [O I]. With increasing distance behind this edge Type I behavior becomes established, and there is a decline of velocity sensitive ratios such as [O III]/[O II] and [O III]/H α . Fesen et al. (1982) suggest that the only way to achieve this type of spatial structure and maintain the assumption of steady flow is to have a spatial stratification of clouds in the ISM on the basis of density. They rightly reject this as unlikely for a well mixed cloud population, and interpret their apparent inability to fit model calculations with observations of line ratios as evidence for the dominance of non-steady flow in the structure of the remnant. Specifically, they suggest that the sizes of the clouds being shocked are too small to contain entire recombination regions, and that the observed stratification comes from looking at less and less ionized parts of the recombination region at greater distances behind the blast wave. The fact that beginning 15-20 arcseconds behind the leading edge of Region I we encounter Type I behavior leads us to interpret the observed structure of Region I as a real gradient in shock velocity, with velocity decreasing with increasing distance behind the leading edge.

Shull and McKee (1979) show the cooling function as a function of hydrogen column density for a 100 km/sec shock with a preshock density

of 10 cm^{-3} . The hydrogen has completely recombined and the metal forbidden and semi-forbidden cooling rate has dropped to $< 1\%$ of its maximum value at a hydrogen column density of $\sim 4 \times 10^{17} \text{ cm}^{-2}$. This corresponds to a distance of $4 \times 10^{16} \text{ cm} = 1.3 \times 10^{-2} \text{ pc}$ in the preshock medium (≈ 3.5 arcseconds at $d = 770 \text{ pc}$). This scale represents an estimate of the size a cloud in the preshock ISM must have to contain enough of a recombination region for the emission to be well approximated by integrated steady flow models. Since the majority of optical emission comes from the portion of the recombination zone far in advance of the $T = 10^3 \text{ }^\circ\text{K}$ point, this estimate is roughly a factor of 10 smaller than similar estimates made using column densities to $T = 10^3 \text{ }^\circ\text{K}$.

The time scale for establishment of this much of the recombination region is $4 \times 10^{16} \text{ cm}/100 \text{ km/sec} = 130 \text{ years}$. A blast wave traveling in the rarefied intercloud medium with a velocity of $\sim 300 \text{ km/sec}$ (relative to the shock driven into the cloudlet) will go $\sim .05 \text{ pc}$ in the amount of time. This distance (~ 15 arcseconds at $d = 770 \text{ pc}$) provides a scale length for the separation of the leading edge of a region where the assumption of steady flow is invalid from the clouds where an optically complete recombination region has been established. It is of the right order to explain the separation between the Type II features along the leading edge of Region I and the onset of Type I behavior, which must be $\geq 15''$. We are not predicting the presence of surface brightness features at a specific distance behind the onset of Type II behavior. Rather, we are saying that surface brightness features present in all lines should not be found within $\sim 15''$ behind an extreme Type II feature. If a feature is seen closer than this behind an extreme Type II feature, it will be Type I.5 (e.g., the separation between the $20''$ and

43" features along S2 and the establishment of other lines behind the [O III] feature at 35" along S3).

There exist a number of plausible mechanisms for producing a real gradient in shock velocity behind the blast wave, apart from density stratification of clouds. One way to achieve this is to have slower shocks last longer. This is entirely plausible since a slow shock will take more time to cross any given sized cloud than a faster shock would take, and the recombination region from the slower shock will still be present when that from the faster shock dies out. Thus, any change in shock strength along the blast front will naturally lead to some stratification when a substantial portion of the front is viewed more or less edge on. Such variations in the strength of the blast wave are likely because the strength of the front will be affected by its interaction with the ISM, with time scales for equilibration with the rest of the remnant equal to the distance scale of the disturbance divided by the sound speed in the post-shock gas. The fact that we see structures (such as the horizontal bar in Region I) which are indicative of a blast wave propagating non-radially provides direct evidence for the presence of such variations in the strength of the blast wave. It is also true that unless the density of clouds decreases faster than the square of their linear dimension increases, then assuming $n_0 v^2$ constant everywhere along the front, slower shocks will tend to last longer. Such a mechanism could also lead to systematic relationships between shock velocity and preshock density which could affect the correlations observed in Figures 11 and 18.

A second mechanism for achieving a velocity gradient is to let the density of a cloud decrease radially from the cloud center. Represent a

cloud by some bell-curve-like enhancement in the density of the ISM. Then when a blast wave hits the cloud, it will initially drive a shock into the low density wings of the cloud. This shock will then propagate into the more dense central regions of the cloud, resulting in a decrease in shock velocity with time, and hence with distance of the shocked cloud behind the blast wave. (The ionization structure of cloudlets in the ISM proposed by McKee and Ostriker (1977) could also play a role here if the ionization of the preshock gas changes as the shock penetrates deeper into cloudlets).

A third mechanism for producing real velocity gradients is to let the pressure driving the shocks into a cloudlet decrease with time after the passage of the blast wave. McKee and Cowie (1975) discuss the interaction of a blast wave with a cloud in the ISM. They show that upon the initial impact of the blast wave with a cloud an overpressure develops at the front of the cloud which drives a bow shock back into the matter behind the blast wave. This overpressure also drives a shock into the cloud with a pressure higher than the pressure driving the blast wave through the intercloud medium. As this overpressure decreases with time, the shock being driven into the cloud will weaken. The time scale for the weakening will be determined either by the decline of the overpressure or the radiative attenuation of the cloud shock itself. Also, as the blast wave passes the cloud, it will drive a shock into the backside of the cloud with a pressure equal to the pressure driving the blast wave through the intercloud medium. This pressure is less than the pressure behind the bow shock of the cloud which drove the initial shock into the cloud. A similar effect could result from the fact that the pressure of the gas behind the blast wave de-

creases to $1/3$ of its peak value at the front (Cox, 1972), although the scale for this effect is somewhat large compared with the scale of the observed velocity gradient. The presence of reflected shocks and shocks which are being driven into cloudlets from all angles could also lead to a "reverberation" of weak shocks, which could add to the diffuse background emission present in lines from low ionic states.

Some combination of the mechanisms presented in the last three paragraphs could reasonably give rise to a decrease in the strength of shocks with time and with distance of the shocked cloud behind the blast wave. Mechanisms of this sort are also attractive because they naturally explain why the structure of the remnant in [O III] is more filamentary than in other lines. Strong [O III] emission due to non-steady flow, low density wings around clouds, or high initial pressures will be confined to a thin region behind the blast wave. The strong [O III] filaments will then be tracers of the recent passage of the blast wave itself, while the less filamentary features, present in all lines, will be longer lived and hence more spread out (Shull et al., 1982).

Other observations seem to support our conclusions about the sizes of clouds present. Parker (1964) and Miller (1974) found that for the observed densities and surface brightnesses of the bright filaments in the Cynus Loop, they must have significant extension along the line of sight (a factor of 10 or more times their apparent width). This, coupled with the fact that individual filaments (such as the "spur") have lateral extensions of up to several arcminutes ($\sim 10^{18}$ cm) suggests that the scale for many clouds in the region is many times greater than the $\sim 10^{16}$ cm scale for clouds in which a shock will never reach steady flow. Additional evidence for this view is found in the existence of

arcs, filaments, and full scale stratified structures (such as the horizontal bar in Region I) at all angles to the radial direction. These features indicate that the blast wave itself has been and is being distorted by its passage through the ISM. This requires the presence of inhomogeneities in the ISM with scales of at least 10^{18} cm. Finally, the fact that line ratios become independent of the detailed structure of the surface brightnesses after the region where non-steady flow is likely to be present can be explained by supposing that surface brightness features are caused by large line of sight projections of large scale shock fronts. That is, surface brightness features which do not correspond to features in ratios of emission lines can be understood if the surface brightness features are due to differences in the line of sight projection of spectrally similar regions. Such a geometry could result from shocks wrapping themselves around clouds which have scales equal to or greater than the observed separation between surface brightness features.

Region IV is a relatively large scale feature which is absent in [O III], present in [O II], and very strong in lines of low ionization states. The scale arguments presented above argue against a non-steady flow interpretation, suggesting that it is an extreme low velocity Type I feature. The absence of [O III] and presence of strong [O I] indicate the presence of shocks with $v \lesssim 60$ km/sec. If this region is in basically the same plane as the Region I features, then the scale of the separation between the blast wave at the leading edge of Region I and this feature is right for the driving pressure for the shocks present to be a factor of 3 lower than that driving the shocks near the leading edge (Cox, 1972).

D. Type II Features — Non-Steady Flow

Within the context of the current discussion, Type II features such as those found in Region II represent relatively clear cases of non-steady flow resulting from the recent encounter of the blast front and relatively diffuse clouds. They satisfy the criterion for non-steady flow of not being well established as surface brightness features in lower excitation lines. The fact that the largest [O III] ratios in the field are associated with this type of feature is also consistent with this interpretation.

The location in the north central part of the field where [O III] arcs serve as boundaries for diffuse [O III] emission also suggests the line of sight nature of the surface brightness features. This location is consistent with a shock wrapping around a cloud with dimensions of approximately 5×10^{17} cm. Since the arcs show a non-steady flow signature, they may also be the lines of intersection between the cloud being shocked and the location of the blast wave in the intercloud medium.

The arcuate features found in Region II may also be due to the passage of the blast wave through a medium which is denser than the intercloud medium holding the 300-400 km/sec shocks responsible for the X-ray emission, but is less dense than the clouds containing the steady flow shocks responsible for Type I emission. In such a medium, the blast wave may be undergoing a process similar to the transition between the adiabatic and snow plow phases of a supernova remnant, as discussed by Cox (1972) and Chevalier (1974). Shocks undergoing such a transition would produce the non-steady flow emission seen (Raymond et al., 1980), and would have velocities higher than those we infer from the optical

data. This also is consistent with the velocities in excess of 130 km/sec needed to explain the UV observations. If this is the case, then the structure of the arcs could be determined by diffraction of the blast wave by clouds. Such a mechanism would explain why the arcs are convex toward the outside of the remnant. The size and radius of curvature of the arcs would also provide a measurement of the size of the clouds present which is consistent with other indications of cloud size discussed above.

UV observations such as those of Raymond et al. (1981) should be particularly sensitive to non-steady flow in Type II features. This is because of their sensitivity to high temperature lines from ions such as O IV, O V, N IV, and N V. If the decrease in shock velocity after the passage of the blast wave is rapid enough, then the ≥ 130 km/sec shocks necessary to produce these lines may slow so quickly as to make association of a complete steady flow recombination region with such a fast shock a rare event. This is consistent with the non-steady flow interpretation previously given to UV observations, except that we predict that such regions will evolve into steady flow shocks with lower velocities.

V. Summary and Concluding Remarks

We find the technique of digital analysis of photographically recorded intensified imagery in the light of strong emission lines reveals a wealth of spatial structure which can be studied in detail with good quantitative accuracy. Comparisons with photoelectric spectrophotometry for two locations in our field indicate the photometric accuracy of the seeing limited spatial structure is comparable to that quoted for photoelectric measurements of significantly larger areas. Small scale (~ 3 arcsecond) statistical errors in line ratios appear to be of the order of 15%. Because of this accuracy, we feel that this technique provides a powerful quantitative tool for examination of both detailed spatial structure of such nebular objects as the Cygnus Loop, per se, as well as those regions between bright filaments which are difficult to investigate photoelectrically.

Comparisons of our observations with previous spectrophotometry of locations throughout the Cygnus Loop indicate that the field observed is a good microcosm of the entire Loop. The presence of smooth loci of points on log-log plots of the correlations between line ratios indicates that the range of physical conditions across the field observed is continuous. Working within the general picture (cf., McKee and Cowie, 1975) that the optical emission from the Cygnus Loop is due to shocks driven into clouds by the supernova blast wave (propagating primarily through the intercloud medium), we propose a picture in which non-steady flow behind shocks with $v \gtrsim 130$ km/sec is responsible for (Type II) features, generally accurate, showing unexpectedly high [O III]/X ratios (and probably also many of the UV observations), while steady flow

recombination regions behind shocks with velocities $\lesssim 120$ km/sec are responsible for (Type I) features which appear in all lines observed. The Type II and Type I features represent extremes in a continuum of classes of features in which optical emission lines from progressively more of the steady flow recombination region become established. The steady flow (Type I) features have gradients in velocity sensitive ratios which are independent of the surface brightness structure. This leads us to suggest both that much of the surface brightness structure is due to line of sight effects, and that mechanisms are operating which result in a real gradient of shock velocities with increasing distance behind the blast wave. Such a steady flow interpretation is further supported by the fact that surface brightness features seen in lines coming from extreme zones of the recombination region (e.g., [O III] and [O I] — where shock velocities are large enough for the production of appreciable [O III] emission) are observed to be spatially coincident within the limits of our resolution.

We also find reasonable agreement between line ratio correlations predicted by models for varying shock velocity and our observations (especially for primarily velocity sensitive ratios). Parameters are given to the fits to these correlations to facilitate spectral comparisons of the Cygnus Loop with other SNR's. Model comparisons are facilitated by use of a log-log format in presenting the data and models, as opposed to straight line ratios used previously in the literature. This format is less sensitive to uncertainties in model parameters than the ratio-ratio format used by previous authors. The "turnover" in certain line ratios predicted to occur at velocities around 100 km/sec is actually observed for a linear feature which has the appearance of a

region of steady flow which is relatively uncontaminated by background or foreground emission. The predominance of shocks with velocities below this value, coupled with the scatter caused by line of sight superpositions of shocks with different velocities (and probably also by variations in spectral characteristics due to variations in other parameters such as preshock density), keep this turnover from being apparent when examining correlations for the entire field.

We are continuing investigations of the Cygnus Loop using the techniques described in this paper, with particular emphasis on the temperature sensitive ratio of $[O\ III]\ \lambda 4363/[O\ III]\ \lambda 5007$. Very preliminary results (in agreement with those of Fesen et al. [1982]) indicate that this ratio is generally flat across the field discussed in this paper, and (like other line ratios) is not strongly correlated with surface brightness structure.

It is our hope that the present and future availability of similar spatially resolved maps of the Cygnus Loop at various wavelengths will help to clarify the detailed relationship between optical, X-ray, and radio emission from the Loop, and will further facilitate the understanding of the physical processes at work in these remarkable objects.

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