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An analysis of the WN shell nebula NGC 6888 using CCD imagery and spectrophotometry

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Rice University, 1991
RICE UNIVERSITY

AN ANALYSIS OF THE WN SHELL NEBULA NGC 6888 USING CCD IMAGERY AND SPECTROPHOTOMETRY

by

PATRALEKHA MITRA

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

DOCTOR OF PHILOSOPHY

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Abstract

We present a model describing the morphology and physical processes in NGC 6888, a 'wind-blown' nebula around the WN6 star HD192163. CCD imagery with the Palomar 1.5m revealed distinct morphological features that were further probed with spectrophotometry using the KPNO #2 telescope + Intensified Reticon Scanner.

Distinctions in morphology in [O III] compared to Hα led to a parametrization into two physical systems: (1). An inner ionized shell observable in all the emission lines, with [N II] $T_e = 8000$ °K, [O III] $T_e = 14,000$ °K and [S II] $N_e = 400$ cm$^{-3}$; (2). The [O III] bubble and rim, visible only in [O III] and characterized by a higher [O III] $T_e = 50,000$ °K. The nebula is found to have 5-10 M$_\odot$ of ionized mass. An extrapolation of [O III] $\lambda$5007 fluxes to IR emission line intensities led to revised values of neutral mass $\sim 40$ M$_\odot$ for the nebula. Of this 3-6 M$_\odot$ is found to be enriched mass, 0.5 M$_\odot$ contributed by stellar wind mass loss and wind swept ISM mass is determined to be $\sim 20-60$ M$_\odot$. Photoionization models demonstrate that the shell is enriched in N and He and depleted in O compared to Galactic H II regions.

These results collectively indicate a scenario that is a combination of several physical processes. A slow wind ejected in an asymmetric fashion from the star is swept up by a fast stellar wind together with the ambient medium, creating the ionized shell. This interaction also creates Rayleigh Taylor instabilities which are determined to be plausible formation mechanisms for the observed knots. The hot gas ($\sim 10^7$ °K) penetrates the nebular material in the NW and SE as there is less ejecta pressure opposing it along the polar axis, and creates the observed [O III] bubbles in the NW and lattice in the SE.
ACKNOWLEDGEMENTS

'Oh but a man's reach should exceed his grasp

Or what's a Heaven for ..........

From childhood I have always, like most astronomers, been fascinated by the mysteries of the great unknown skies. My thesis is the culmination of a lifetime desire to be an astronomer. In that sense, I have a lifetime of relatives, friends, and teachers to thank who have helped in ways, big or small, by encouraging, supporting and always letting me keep the stars in my eyes. This list is therefore as limitless and open-ended as any thesis, and any omissions are due to space-time limitations.

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I. INTRODUCTION

MOTIVATION FOR THESIS

Luminous massive stars, although few in number, play a dominant role in the chemical evolution and state of the interstellar medium. These objects have a significant effect on the ambient interstellar medium because during their evolutionary cycle they return highly processed material to the ISM, through stellar wind, stellar ejecta or demise as a supernova. Optical (Conti and Leep 1974) and ultraviolet (Smith 1970) observations show that stars of spectral type earlier than B2 have strong stellar winds with terminal velocities of order \( V \sim 1500 - 3000 \) km s\(^{-1}\) and rates of mass loss \( \dot{M}_w \) approaching \( 10^{-6} \) \( M_\odot \) yr\(^{-1}\). Such winds, over the lifetime of the star are capable of imparting a mechanical energy of order \( 10^{50} \) ergs to the surrounding interstellar medium, which is comparable to that in supernova shells. Mass loss in the form of stellar winds also create interstellar bubbles and produce large amounts of hot, ionized gas around the star. Studies of the chemical composition and physical parameters of shell nebulae and planetary nebulae, etc. around such stars therefore result in a more detailed comprehension of mass loss rates, and the chemical make-up of ejecta which eventually affect the ISM. Study of such shells or bubbles also describe the interaction between massive stars and their environment.

In this thesis we study the optical emission of the shell created by and located around such a luminous massive star HD 192163, a WN 6 type star (V = 7.7 mag.). A comprehensive study of this nebula helps us to understand the physical properties of such 'wind-blown' shells, and the interaction between massive stars and their environment. In this chapter we review types of emission nebulae, the process of evolution of wind-blown bubbles, classification of the types of shells around WR stars, optical emission from such nebulae, and the salient features of NGC 6888 that make it a
good candidate for the study of such interactions.

I.1. **NEBULAE AROUND LUMINOUS STARS**

An emission nebula is a low density ionized plasma, large in size compared to stellar dimensions. Many varieties of these objects are found in nature. Emission nebulae can be divided into three main types: diffuse nebulae or H II regions, planetary nebulae (hereafter PN), and supernovae remnants. H II regions are regions of interstellar gas that are excited by central hot stars, O or B-type Pop. I stars. The effective temperatures of these stars are in the range $3 \times 10^4 \degree K < T* < 5 \times 10^4 \degree K$, and throughout the nebula, H is ionized. Typical densities in the ionized part are around $10 - 10^2 \text{ cm}^{-3}$. The central stars of PN are old stars, that are hotter - $T* \sim 5 \times 10^4 \degree K$ to $3 \times 10^5 \degree K$. Typical PN have a higher degree of ionization than H II regions. Supernova remnants have strong nonthermal spectra. In these objects, collisional ionization and not photoionization is the dominant ionizing process.

Such gaseous nebulae are interesting because of several reasons. Firstly, their observable spectra can be interpreted in terms of well defined physical processes. Also gaseous nebulae provide clues about stellar birth, evolution and demise, nucleosynthesis in stars, composition of the ambient interstellar medium, and structure and evolution of galaxies.

I.1.a. **Wind-Blown Shells**

Some of these nebulae are wind-driven such as a). bubbles around single OB stars (with $R_{nub} > 10 \text{ pcs}$) or "superbubbles" with $R > 100 \text{ pcs}$. (b). Ring nebulae around WR stars (c). nuclei of planetary nebulae.

The development of a wind-driven circumstellar shell follows a scenario akin to that of a supernova shell. Initially, there is a free expansion phase at wind velocity for
a few centuries, followed by a period of adiabatic expansion for a few thousand years during which radiative losses by the gas are not important. At some point, i.e., at the 'snowplow phase', the radiative losses do become important and this phase lasts through most of the star's lifetime.

This phase is described by Castor et al (1975) as a four zone structure consisting of:

1). Zone A: a hypersonic stellar wind with density \( \rho_w (R) = \dot{M}_w / 4\pi R^2 V \), (2). Zone B: following that, a hot isobaric shocked stellar wind region mixed with a small fraction of swept-up interstellar gas, (3). Zone C: A thin, dense cold shell at radius \( R_s \) containing most of the swept-up interstellar gas, (4). Zone D: outer ambient interstellar gas of density \( \rho_0 \), expanding at velocity \( \dot{R}_s \).

The theory of McCray et al. (1977) assumes an idealized interstellar medium of uniform density \( \rho_0 = \mu M_H N_0 \), where \( \mu \) is the mean molecular weight. Further, the wind is isotropic with a constant energy flux \( L_w = 1/2 \dot{M}_w v_w^2 \) ergs/sec. This wind produces a cavity that bulldozes the surrounding interstellar medium into a thin shell of mass \( M_s(t) = (4\pi/3) R_s^3 \rho_0 \), where \( M_s(t) >> M_v t \), the mass of the material in the wind. The motion of the shell, i.e. region C is given by:

\[
\frac{d}{dt} [M_s(t) V_s(t)] = 4\pi R_s^2 P_{\text{int}}
\]

where \( P_{\text{int}} \) is the internal pressure in the cavity. The dynamics of the shell is specified by \( P_{\text{int}} \). A critical bifurcation in the theoretical models occurs with two different idealized assumptions about \( P_{\text{int}} \). If we assume (a) conservation of thermal energy of the shocked stellar wind, then:

\[
P_{\text{int}} = \frac{\text{energy}}{\text{volume}} = \frac{1}{3} \frac{L_w}{4\pi} \frac{3 t}{R_s^3}
\]
The radius $R(t)$ in parsecs, of the outer shell is given by

$$R_s(t) = 27 N_0^{1/5} \left( \frac{L_w}{L_0} \right)^{1/5} \left( \frac{t}{t_0} \right)^{3/5} \text{ pc}$$

(1.3)

where $L_0 = 10^{36}$ erg/sec, $t_0 = 10^6$ years, and $L_w$ is the energy in the stellar wind, typically $10^{36}$ erg/sec. The age of the structure is $t \sim 0.6 R_s / V_s$. Fig 1.1 (McCray 1977) demonstrates this process. The stellar wind $W$ encounters a shock at some radius $R_1$, as shown in the figure. The shocked gas $C$, is heated to coronal temperatures, in excess of $10^6 K$. A sharp temperature gradient exists across the interface between the coronal gas and the compressed interstellar medium material. Heat flows from the hot coronal gas into the cooler outer shell by electron conduction. Gas evaporates from the shell and flows inwards, thus lowering the temperature, increasing the density and enhancing the radiative losses of region $C$. The radiative loss from $C$ increases until it becomes comparable with energy loss in the wind. At this point, the coronal region starts to collapse, therefore $R_1$ increases.

At this epoch, that occurs at time $t_{rad}$ the dynamics can be better described by a 'momentum conservation' model, in which it is assumed that internal thermal energy is radiated away and the momentum of the wind is conserved as it impinges on the shell. Therefore:

$$p_{inw} = \rho_w V_w^2 = \frac{M_w V_w}{4 \pi R^2}$$

(1.4)

and

$$R(t) = 16 \left( \frac{L}{L_0} \right)^{1/4} \left( \frac{1000}{N_0} \right)^{1/4} \left( \frac{t}{t_0} \right)^{1/2} \text{ pc}$$

(1.5)
Mc Cray (1983) finds:

\[ t_{\text{rad}} = 0.5 \frac{R_s}{V_s} \]  

Application of the 'energy conserving' model as opposed to the 'momentum conserving' one give very different results when observations are used to deduce properties of the wind. In general, shells derived from the momentum conserving case have less energy, smaller radii, and smaller velocities, than those derived by the energy conserving case.

1.1.b. WR Shell Nebulae

A few years ago a new class of nebulae, i.e. nebulae around WR stars joined the previously known more familiar class of nebulae generated by stars (planetary nebulae, novae and supernovae). These are examples of stellar winds and even ejecta impinging on the interstellar medium. They are loosely defined as "arcs of nebulosity centered on and ionized by WR stars". The existence of ring nebulae around WR stars is indicative of interaction between the central WR stars and the ambient interstellar medium around them. Chu (1981a, 1981b) identified 15 such WR ring nebulae in the Galaxy. More than 20 WR-rings and 13 Of-rings are known now.

Observational studies of such WR nebulae have been relatively scarce, while radio observations have concentrated mainly on the brighter nebulae. Typically, the radii of the shells lie between 3 and 10 pcs, the expansion velocities between 20 and 80 km/sec, and lifetimes between \( 2 \times 10^4 \) and \( 2 \times 10^5 \) years. The masses derived for such nebulae range from \(< 1 \, M_\odot\) for M1-67 (Israel and Felli 1976) to much larger masses such as \(100 \, M_\odot\) in RCW 104 (Chu 1982). Nitrogen and Helium overabundances have been previously observed in some nebulae such as NGC 6888 (Kwitter 1981) and NGC
2359 (Kwitter 1979). Extended Wolf-Rayet shells appear to be in the momentum-conserving case, which means that the inner regions must have more than several solar masses in order to radiate away the thermal energy of the shocked wind. These types of shells are associated with W-R stars and not ordinary O stars, as the former are believed to be massive highly evolved objects that may have passed through the M supergiant phase and have lost their outer envelopes. Their vigorous winds \((V_w \sim 2500 \text{ km/sec}, L_w \sim 5 \times 10^{37} \text{ ergs/sec}, \text{and} \dot{M}_w \sim 3 \times 10^{-5} \text{ M}_\odot/\text{yr})\), impinge not only upon the local ISM but in some cases also on debris ejected during the previous red supergiant phase of the star itself.

I.1.c. **Classification**

Chu (1981) classified such WR shells in terms of their formation mechanisms, after a systematic search and morphological and kinematical studies of 15 such WR ring nebulae.

The two selection criteria used defined the WR ring nebula as a small symmetric nebula around a WR star with (a) The WR star located at a preferred position inside the boundary of the nebula, consistent with possible formation mechanisms (b) The WR star as the only important excitation source for the nebula. Chu classified the nebulae into three categories: R - Radiatively excited H II regions which includes \(R_s\)-shell structured and \(R_a\)-Amorphous H II regions; E - Stellar ejecta; and W-Wind-blown bubbles. Further, a correlation between spectral types of the WR stars and the nebular type was found. \(R_a\) nebulae were found to be preferentially associated with late-type WN stars, \(R_s\) type with WC stars, E-type stars with WN8 and W-type with early WN stars. This observation supports two deductions i.e. a) The wind turning-on time for late-type WN stars must be more recent than early-type WN stars (b). The WC stars are in much older environments than WN stars. The characteristics of each of the categories are as
follows:

i). R - RADIATIVELY EXCITED H II REGIONS

R-type nebulae are characterized by spectra that indicate radiative excitation. The expansion velocities as derived from line widths are subsonic and similar to those in normal H II regions. R-types are further divided into two morphological subtypes: \(R_a\) - amorphous H II regions and \(R_s\) - shell structured H II regions (limb brightening present in these).

Massive hot stars formed in neutral clouds ionize the ambient medium and form amorphous nebulae. The massive stars can then interact with the H II region by stellar winds or by supernova ejecta. This shell eventually slows down and forms a \(R_s\) type nebula. For an ambient density \(\sim 1 \text{ cm}^{-3}\), and a shell internal energy of \(10^{50} \text{ ergs}\), it requires about \(10^6\) years for the expansion of a wind-blown bubble to slow down to 10 km s\(^{-1}\). Therefore, the dynamic age of an \(R_s\) nebula is greater than the lifetime of the WR phase, implying that the nebula is not solely the result of the WR star interacting with the ambient medium.

ii). E - STELLAR EJECTA

This type is characterized by a clumpy appearance, possibly due to Rayleigh-Taylor instabilities or anisotropic injection; and also by an irregular velocity field. Stellar ejecta are usually short-lived. The densities in the ejecta are usually higher than \(10^3 \text{ cm}^{-3}\), and therefore exceed that of the ambient interstellar medium. This causes the ejected shell to expand slowly and dissipate. However, if such an ejected blob is enclosed in a wind-blown bubble it can survive longer, as then the ambient pressure is that inside the bubble, which is higher. The destruction of the blob then occurs because of evaporation due to heat conduction on the surface, the evaporation time-scale \(\sim 5 \times 10^4\)
yr. Therefore E-type nebulae can be found only if the ejection has occurred recently or the ejecta is enclosed in a bubble. Examples: M1-67 has younger ejecta in a normal environment, and RCW 58 has older ejecta inside a bubble.

iii). W - WIND BLOWN BUBBLES

W-type nebulae are characterized by filaments and sheets of gas around the exciting star. The age is given by \( T = \eta \times \text{radius/ expansion velocity} \), where \( \eta \) is around 0.5 or 0.6 for the energy conserving or momentum conserving case respectively. This age is less than the lifetime of the WR phase of the central star, which indicates that the bubble is really blown by the star. The star is found either at the geometric center, or offset towards the brightest region of the nebula. Brighter regions are higher in density, and therefore less accelerated by the wind, thus found closer to the star. Thin sheets exist as wind blown shells that are free of Rayleigh Taylor instabilities.

I.2. OPTICAL EMISSION FROM NEBULAE

Surface brightness and ratio images of wind-blown shells or nebulae can convey a wealth of scientific information about the physical parameters and morphology of the nebula.

There are intrinsic differences in the spectra generated by gaseous nebulae excited by shock waves compared to those excited by radiation (Raymond 1979).

The passage of high velocity winds (> 80 km sec \(^{-1}\)) through the ambient interstellar medium or previous ejecta leads to collisional excitation, photoionization, and subsequent emission-line cooling over the whole range of wavelengths from the far-ultraviolet to the far-infrared. In shells associated with WR stars McCray (1983) suggests that vigorous winds with \( V_w = 2500 \, \text{km s}^{-1} \) and \( \dot{M}_w = 3.5 \, \text{M}_\odot/\text{yr} \) impinge not only on the local ISM, but rather on debris ejected during the red supergiant phase of the
star itself. In individual nebulae such as NGC 6888 therefore, there are spatial variations of relative line intensity. Spatial locations of recombination lines or forbidden lines are dependent on physical properties of the shocked gas. The location and relative brightnesses of these lines give an idea of the modes of ionization, the ionization structure, the chemical composition and physical parameters like the electron temperature and density.

For photoionized nebulae, the ionization structure indicated by different emission lines and relative ratios in the nebula is dependent on the mean ionization parameter at a given point in the nebula. The mean ionization parameter \( U \), is defined by

\[
U = \frac{Q(H^0)}{4\pi R_s^2 N c},
\]

where \( Q(H^0) \) gives the number of ionizing photons available, \( R_s \) is the Stromgren radius and \( N \) is the gas density.

The emissivity of recombination lines are given by (Osterbrock 1974):

\[
4\pi j_\lambda = N_e N_i \alpha(N_e, T_e, \lambda) E(\lambda)
\]

(1.7)

where \( N_i \) and \( N_e \) are the ionic and electron density respectively, \( E(\lambda) \) is the energy of the transition, and \( \alpha(T_e, N_e, \lambda) \) is the recombination coefficient. For a given \( N_e \) and \( T_e \), the intensity of recombination lines is a constant. In the case of H\( \alpha \), eqn. 3.1 implies that \( j(H\alpha) \) is proportional to \( N_e^2 \), as \( N_e = n_i \).

For collisionally excited forbidden lines, on the other hand, the emissivity \( J \) of the transition from an upper state \( j \) to a lower energy state \( i \) is given by:

\[
4\pi J_{ij} = 8.63 \times 10^{-6} N_e N_i \Omega_{ij} T_e^{-1/2} g_i^{-1} b_{ij} E_{ij} \exp\left(-\frac{E_{ij}}{kT_e}\right)
\]

(1.8)

where \( \Omega_{ij} \) is the collision strength, \( b_{ij} \) is the branching ratio, \( g_i \) is the statistical weight
weight of level i. The ratio of emissivities is proportional to the particle density, i.e. the ionization level integrated along the line of sight.

1.3. **NGC 6888, A WR SHELL**

NGC 6888 regarded as a prototype of its class, is a knotty shell nebula located around and associated with the central Population I WN 6 star HD 192163 (M_v = -4.4 for a distance = 1.45Kpc). It is among the largest in apparent size (7.6 x 5.0 pc) and highest in Hα surface brightness. It has a very strongly developed and nearly complete filamentary structure, compared to other such nebulae. In Chu's (1981) WR ring nebulae classification (preceding discussion), NGC 6888 is noted as a prototype "wind blown" type nebula. NGC 6888 has thus been a target for many observational studies. Some of the major studies include optical spectrophotometry (Sabaddin et al. 1977, Parker 1978, and Kwitter 1981), radio continuum and Hα + [N II] maps by Wendker at al (1975), Fabry - Perot observations by Treffers and Chu (1981), IRAS imaging (Van Buren and McCray 1988), and soft X-ray emission using the EINSTEIN observations (Bochkarev 1988). Kwitter (1981) suggested nitrogen and helium enrichment in some of the brighter knots of NGC 6888 by factors of 9 and 2 respectively, compared with the Orion nebula. These observations indicate distinctly different physical phenomena in this object. NGC 6888 is therefore, a potential wealth of data as regards interactions of winds and stellar ejecta with the ambient ISM, compositional and abundance studies, studies of the exciting WR stars, etc.

1.4. **THESIS OBJECTIVES**

In this study we present the first composite quantitative analysis of the morphology, the composition, and the physical processes in NGC 6888. To this end, we have presented and analysed our own high resolution emission-line imagery and
spectrophotometry of this object. We have compared other studies of this object in the optical and other wavelengths and fit those results into our own picture, to give a complete and detailed model. Previous studies of shell nebula have been limited to low spatial resolution spectrophotometry and narrow-band photographs.

In Chapter II, our imagery and spectrophotometry observations are presented, and the data reduction process is discussed.

In Chapter III the final results derived from our observations are presented. In particular, we have discussed the morphological features in the surface brightness as well as the ratio images in macroscopic and microscopic detail. This study helps us to understand specific features in the images, as well as compare features from one emission-line image to another. These features suggest specific formation, ionization and interacting mechanisms that have created the nebula. From our spectrophotometry results we have derived diagnostics like $T_e$ and $N_e$, and succeeded in separating the nebula into two distinct zones of different morphologies and ionization levels. Using these diagnostics we have also studied the ionization structure of the nebula, the abundances, and thus the chemical composition in the nebula.

In Chapter IV we have studied the physical structure in terms of the shell mass, thickness, radius and density; the age of the nebula and the geometry and orientation of the nebula, from our imagery and spectrophotometry results derived in Chapter III. We have also attempted to spatially resolve the ionization structure and study the interactions with the ambient medium. The total mass of the nebula was derived, in terms of the enrichment mass, the swept up interstellar mass, and mass from the stellar wind. The size and shape of the H$\alpha$ 'knots' were used to determine the physical processes that could create and maintain them. In this chapter a photoionization model was also derived that demonstrated the closest fit to the observed results. This model helped to determine the physical processes responsible for the ionization and physical
structure that lead to the observed emission.

In chapter IV we have attempted to correlate results obtained from other studies in the radio, X-Ray and Infra-Red wavelengths, with the results we have obtained from studies in the optical. We have related the results to the true geometry of the object, by incorporating radial velocity measurements and subsequent morphological models obtained with Fabry-Perot observations.

Finally, we also present a plausible scenario for the formation and evolution of this nebula that incorporates all the observed results (from this study as well as others discussed), and summarise the main results obtained in the previous chapters.
Figure 1.1. Schematic diagram of an interstellar bubble indicating the regions and boundaries of the flow.
II. OBSERVATIONS & REDUCTIONS

II.1a  CCD IMAGERY OBSERVATIONS

Observations of NGC 6888 were made in July 1987 and July 1988 using the Palomar 60 inch Ritchey-Chretien f/8.6 telescope, with a focal-reducing lens system that produced an effective f-ratio of f/1.66 attached to a TI 800 x 800 CCD array (PFUEI) as the detector. The CCD chip is identical to those on the HST Wide-Field Planetary Camera imaging system. The advantage to CCD imagery over photographic imaging is the wide dynamic intensity range afforded by sixteen bit data values and also the very high sensitivity of the CCD and consequently shorter exposure times required.

The field covered in 1987 was 16' square with a pixel resolution of about 1.19"", centered at 20h 10m 35.3 s (1950) and 38° 14' 59" (1950). In July 1988 another set of observations was taken with the field covered shifted more towards the south of the WN star, centered at 20h 10m 18.9 s (1950) and 38° 7' 17" (1950). The idea was that the two sets of observations together would give a composite picture of the nebula and the extended emission around it, as the optical emission covers about an 18' by 12' area.

The optical set-up at the telescope's backend consisted of specific 3 inch diameter filters placed inside the optical collimator. The collimator was used to produce a parallel light beam for the CCD camera lens, whose focal plane coincided with the position of the CCD chip. The effective focal ratio of the system was reduced from the intrinsic focal ratio of the 60 inch telescope, since the collimator and the CCD camera lens had unequal focal lengths, where effective focal ratio:

\[ \text{EFR (system)} = \frac{\text{F.R. (telescope)} \times \text{F.L. (camera)}}{\text{F.L. (collimator)}}. \]

where:  \( \text{FR (telescope)} = 8.75 \)

\( \text{FL (collimator)} = 308 \text{ mm} \)

\( \text{FL (camera)} = 58 \text{ mm} \).
Thus the focal ratio of the arrangement was f/1.66, i.e. a very fast system capable of achieving very high image densities for diffuse objects like galaxies or nebulae, and also giving a wide field of view (16' square).

The various filters used to produce the separate images were 3 inch interference filters centered on specific wavelengths in both the red and green part of the spectrum. The bandpass center, width and associated emission or continuum line are listed in Table 2.1. The filter transmission wavelengths are centered on characteristic emission lines (including forbidden lines) of H II regions, or adjacent line-free continuum bands. The data also included "flat fields" of uniformly illuminated regions of the dome, in order to compensate for nonuniformities in the detector sensitivity to avoid extraneous artifacts produced in the images by detector flaws.

<table>
<thead>
<tr>
<th>Wavelength (Å)</th>
<th>Width (Å)</th>
<th>Emission Line</th>
<th>Integ. Time (North)</th>
<th>Int. Time (South)</th>
</tr>
</thead>
<tbody>
<tr>
<td>4869</td>
<td>31</td>
<td>1st Hydrogen Balmer</td>
<td>1500s</td>
<td>1500s</td>
</tr>
<tr>
<td>5005</td>
<td>30</td>
<td>Forbidden [O III]</td>
<td>1200s</td>
<td>1200s</td>
</tr>
<tr>
<td>4805</td>
<td>75</td>
<td>Green Continuum I</td>
<td>200s</td>
<td>200s</td>
</tr>
<tr>
<td>5103</td>
<td>98</td>
<td>Green Continuum II</td>
<td>200s</td>
<td>200s</td>
</tr>
<tr>
<td>6564</td>
<td>15</td>
<td>Hydrogen Alpha</td>
<td>500s</td>
<td>500s</td>
</tr>
<tr>
<td>6584</td>
<td>14</td>
<td>Forbidden [N II]</td>
<td>500s</td>
<td>400s</td>
</tr>
<tr>
<td>6584</td>
<td>14</td>
<td>Forbidden [N II]</td>
<td>100s</td>
<td></td>
</tr>
<tr>
<td>6450</td>
<td>104</td>
<td>Red Continuum I</td>
<td>75s</td>
<td>75s</td>
</tr>
<tr>
<td>6650</td>
<td>100</td>
<td>Red Continuum II</td>
<td>75s</td>
<td>75s</td>
</tr>
<tr>
<td>6730</td>
<td>36</td>
<td>Forbidden [S II]</td>
<td>1200s</td>
<td>1000s</td>
</tr>
</tbody>
</table>
II.1.b  CCD-IMAGERY DATA ANALYSIS:

The data was reduced at Rice University using a SUN 3/280 SC workstation, with a color 1152 x 900 8-bit image display, therefore the 800 x 800 pixel square images could be displayed in their full size. The IRAF V2.6 and later V2.8 (Image reduction and analysis facility) image processing software was used for reducing the data. The data reduction process was done in several steps with the final goal being the production of images which contain purely the light emitted from the nebula without being contaminated by sky, starlight or background light. The steps in order are the following, where the IRAF routine names are italicised:

i). Bias Subtraction

CCD detectors have very high quantum efficiency. The noise level of a CCD detector is very small compared to other detectors and photographic methods. Along with the noise, the CCD detector operates with a small D.C. offset voltage applied to the bins. To get an uncontaminated image, this bias level was removed from the data, using the IRAF routine 'bias'. A 16 x 800 pixel wide bias strip along the left side of the image does not receive any illumination during the exposure, and therefore provides a reference for determining the bias level. An average of all the pixel values in this overscan bias strip was subtracted from each of the pixels, for every image.

ii). Flattening

In order to remove distortions created by the detector, each pixel had to be further divided by the corresponding pixel in a bias subtracted flat (dome flat) image using the same filter with the IRAF routines 'flatten' and 'flatdiv'. This division compensated for the variation in sensitivity over areas of the detector, in proportion to the original distortion. An average of two flats taken at the beginning and the end of the night
was used. The image divided by the dome flat was normalized back to the average intensity of the original image.

iii). Alignment

Images successively taken during even the course of one night (and even worse, on different nights) were shifted and rotated with respect to each other, due to telescope motion and flexure between exposures, and filter distortions. It was therefore necessary to properly align the images with respect to each other before any operations were performed between separate images.

The first step in the alignment process involved the identification of about 30-40 bright, but not saturated stars that were well distributed over the field in all the images. The x and y coordinates of these stars in pixel units were identified using 'center' in the 'APPHOT' package, which calculates the centroid of a specified 5 by 5 pixel box. After the same star coordinates were identified in all the images, then lists containing the x and y of the reference image and the image to be aligned were created in a four column form 'xref yref ximage yimage'. These lists were then used to map one image to another, as described further.

The alignment was done using the iraf routines 'Geomap' followed by 'Geotran'. Geomap computes the transformation required to map the coordinate system of the reference image to the coordinate system of the input image. The transformation has the form:

\[ xin = f (xref, yref) \]
\[ yin = g (xref, yref) \]

where the functions f and g used were Legendre polynomials of order three. The subroutine 'Geotran' further corrected the image for geometric distortion (scale shift and rotation) using the coordinate transformation determined by 'Geomap'; a third order
Legendre polynomial transformation was used and the intermediate pixels values were interpolated with linear interpolation, and sampled with respect to the boundary of the nearest neighbour. All the emission line images and the red continuum images were aligned to the green continuum, GC2 image. Overall, the alignment process (though overly time-consuming with the old IRAF 2.6), after detailed and thorough measurements and centering processes gave aligned images which were correct to within 0.02-0.5 pixels, as in Table 2.2. Table 2.2 gives the number of stars used for each alignment, and the mean shift in x and y for the line image with respect to the continuum image. The [O III] image of the northern field of view taken in the second observing session (July '88), was aligned to the green continuum image of July 1987; and significant rotational transformation problems were encountered here; but forcing a lateral shift to the image first solved this problem. The [N II] long and short exposure images were separately aligned and time averaged before continuum subtraction, to give a single [N II] image.

<table>
<thead>
<tr>
<th>Image</th>
<th># of stars</th>
<th>Mean dx</th>
<th>Mean dy</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hα</td>
<td>34</td>
<td>0.12</td>
<td>0.09</td>
</tr>
<tr>
<td>Hβ</td>
<td>35</td>
<td>0.10</td>
<td>0.05</td>
</tr>
<tr>
<td>[N II]</td>
<td>35</td>
<td>0.07</td>
<td>0.08</td>
</tr>
<tr>
<td>[O III]</td>
<td>25</td>
<td>0.15</td>
<td>0.11</td>
</tr>
<tr>
<td>[S II]</td>
<td>25</td>
<td>0.12</td>
<td>0.10</td>
</tr>
</tbody>
</table>

TABLE 2.2 ALIGNMENT TABLE
v). **Continuum Subtraction**

The nebulosity associated with the actual object is also obscured by light contributed by numerous background and foreground stars in the same field. This starlight contribution is distinguishable from the nebular emission, as the majority of the stars have approximately flat radiation curves.

The narrowband (15-30 Å) filter images centered on the specific emission lines recorded mainly the nebular emission-line light. Wide-band (~100 Å) exposures centered on adjacent line-free continuum bands measured the stellar as well as the nebular contribution.

In order to remove the continuum light from the narrowband emission image, a scaling factor (S.F.) relating the two types of images had to be determined. This S.F. was determined from the ratio of the intensities of individual stars (performed for about 25-40 stars) in a given emission-line image to that in the associated continuum images. The stellar intensities were sampled by measuring 5 x 5 pixel boxes centered on the stars, and 10 x 10 around that (inclusive); therefore the net continuum contribution was obtained from the subtraction of the latter from the former. Table 2.3 gives the normalization constant, number of stars used, and standard deviations in the S.F. for each image. The specific continuum image (green continuum for [O III], Hβ and red continuum for [N II], [S II] and Hα) was then multiplied by the normalization factor and subtracted from the emission-line image, to give the final continuum subtracted image. For this procedure, IRAF arithmetic commands such as 'imarith' and 'imdivide' were used.

A problem that we faced was that our wide-band RC2 (6650/100) image was found to be contaminated by [N II] λ6584 to a significant extent. This was solved by first calculating an [N II] 'contamination' image by subtracting a normalised RC1 image
(multiplied by a factor of 0.9565 found by measuring specific stars in both RC1 and RC2 images) from the original RC2. This [N II] contamination image was then subtracted from the original RC2 image to give a corrected RC2 image. For continuum subtraction purposes finally, RC1 and the corrected RC2 were averaged, and it was this final averaged RC image that was used for the continuum subtraction of Hα, [N II] and [S II] images. Similarly, an average (time averaged) image of GC1 and GC2 was used for the continuum subtraction of Hβ, and [O III].

<table>
<thead>
<tr>
<th>Image</th>
<th># of stars</th>
<th>North N.C.</th>
<th>σ N.C.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hα</td>
<td>30</td>
<td>0.78 (Hα/ RC)</td>
<td>0.09</td>
</tr>
<tr>
<td>Hβ</td>
<td>30</td>
<td>1.79 (Hβ/ GC)</td>
<td>0.13</td>
</tr>
<tr>
<td>[N II]</td>
<td>29</td>
<td>0.49 ([N II]/ RC)</td>
<td>0.04</td>
</tr>
<tr>
<td>[O III]</td>
<td>32</td>
<td>1.71 ([O III]/ GC)</td>
<td>0.16</td>
</tr>
<tr>
<td>[S II]</td>
<td>25</td>
<td>2.31 ([S II]/RC)</td>
<td>0.35</td>
</tr>
<tr>
<td>south Hα</td>
<td>25</td>
<td>0.72 (Hα/ RC)</td>
<td>0.09</td>
</tr>
<tr>
<td>south Hβ</td>
<td>25</td>
<td>1.31 (Hβ/ GC)</td>
<td>0.09</td>
</tr>
<tr>
<td>south [N II]</td>
<td>25</td>
<td>0.70 ([N II]/ RC)</td>
<td>0.06</td>
</tr>
<tr>
<td>south [O III]</td>
<td>24</td>
<td>1.69 ([O III]/ GC)</td>
<td>0.10</td>
</tr>
<tr>
<td>south [S II]</td>
<td>24</td>
<td>4.88 ([S II]/RC)</td>
<td>0.14</td>
</tr>
</tbody>
</table>

iv). **Sky Subtraction**

The diffuse background skylight, mainly contributed by the scattered light from large cities around (Palomar is close to Los Angeles and San Diego!) and by airglow in the upper atmosphere, had to be subtracted from the images, as this sky
background could be as high as 5% of the maximum intensity levels on our data. This is just a second order correction as most of the sky had already been subtracted during continuum subtraction. In case of the south field images though, the sky had been subtracted before the continuum subtraction. Sky subtraction may appear as a superfluous step, but is a necessary step as the given filter may respond differently to sky and stellar continuum radiation.

Sky subtraction was performed by sampling $7 \times 7$ cross-section pixel boxes of a few ($\sim 4$) relatively stellar and nebular continuum free regions all around the image, which gave an average (and standard deviation) of sky values for all images. Only a few regions could be sampled for sky subtraction as nebular emission filled most of the image area, and nebula-free areas were rare. Actually, as this bubble lies in the superbubble associated with the Cygnus OB1 association, the sky value should be non-zero even in the surrounding regions. This sky value was then subtracted from each image (shown in Table 2.4) using 'imarith', to give images free from sky contamination.

<table>
<thead>
<tr>
<th>Image</th>
<th>#1</th>
<th>#2</th>
<th>#3</th>
<th>#4</th>
<th>average</th>
<th>$\sigma$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hα</td>
<td>474</td>
<td>453</td>
<td>502</td>
<td>464</td>
<td>473</td>
<td>18.2</td>
</tr>
<tr>
<td>Hβ</td>
<td>174</td>
<td>195</td>
<td>212</td>
<td>191</td>
<td>193</td>
<td>13.5</td>
</tr>
<tr>
<td>[N II]</td>
<td>152</td>
<td>119</td>
<td>127</td>
<td>148</td>
<td>137</td>
<td>13.9</td>
</tr>
<tr>
<td>[S II]</td>
<td>52</td>
<td>29</td>
<td>65</td>
<td>51</td>
<td>49</td>
<td>12.9</td>
</tr>
</tbody>
</table>
vi. Calibration

The emission-line images were calibrated from spectrophotometric measurements of the same lines from observations of NGC 6888 by the author and R.J. Dufour at KPNO in July and Sept. 1989 (further discussed in next section). Pixel boxes of sizes (30 x 7 pixels) closely approximating the size of the slit used (35.6 x 7.8") were integrated to give total fluxes (in counts) enclosed in each such box, for the same positions as the spectrophotometric observations (about 14 positions for each image). The calibration constant was then determined for each line image by dividing the summed (after scaling to the relative slit areas) pixel flux values for all these positions into the spectrophotometry emission-line flux values (in ergs cm\(^{-2}\) sec\(^{-1}\) \(\text{Å}^{-1}\)) of the same emission line for each position. The continuum subtracted image was finally multiplied by the calibration constant to give the calibrated image. The calibration constants (in \(10^{18}\) ergs cm\(^{-2}\) sec\(^{-1}\) \(\text{Å}^{-1}\)) and standard deviation in calibration constants for each image is presented in Table 2.5.

The 1988 (i.e. offset to the South, henceforth known as the 'South') images were also scaled against the North (1977) images for calibration processes. About 10-12 knots and other recognizable features in the overlapping section of the two images were used to determine a scaling factor to normalize the 'South' images to the 'North' images in the corresponding emission-line filter. The South images were then further multiplied by the calibration constants determined earlier for the North images, to obtain final images that were transformed to the zero point of the spectrophotometric observations.
Table 2.5 CALIBRATION CONSTANTS (10-18 ergs cm\(^{-2}\) sec\(^{-1}\))

<table>
<thead>
<tr>
<th>position</th>
<th>H(\alpha)</th>
<th>H(\beta)</th>
<th>[N II]</th>
<th>[O III]</th>
<th>[S II]</th>
</tr>
</thead>
<tbody>
<tr>
<td>NE1-W</td>
<td>1.20</td>
<td>0.65</td>
<td>1.99</td>
<td>1.61</td>
<td>2.02</td>
</tr>
<tr>
<td>NE1-E</td>
<td>1.21</td>
<td>0.68</td>
<td>1.95</td>
<td>1.41</td>
<td>1.51</td>
</tr>
<tr>
<td>O3spur-W</td>
<td>1.47</td>
<td>0.88</td>
<td>2.51</td>
<td>1.91</td>
<td>-</td>
</tr>
<tr>
<td>NW1-W</td>
<td>1.29</td>
<td>0.82</td>
<td>2.06</td>
<td>1.79</td>
<td>-</td>
</tr>
<tr>
<td>W1-W</td>
<td>1.10</td>
<td>0.63</td>
<td>1.95</td>
<td>1.39</td>
<td>-</td>
</tr>
<tr>
<td>NW2-W</td>
<td>1.30</td>
<td>0.78</td>
<td>2.36</td>
<td>1.61</td>
<td>-</td>
</tr>
<tr>
<td>NE2-W</td>
<td>1.40</td>
<td>0.85</td>
<td>2.97</td>
<td>1.62</td>
<td>1.34</td>
</tr>
<tr>
<td>NO3-15&quot;-W</td>
<td>0.97</td>
<td>0.64</td>
<td>1.39</td>
<td>1.60</td>
<td>1.06</td>
</tr>
<tr>
<td>NO3-30&quot;-W</td>
<td>1.42</td>
<td>0.80</td>
<td>2.28</td>
<td>1.64</td>
<td>2.66</td>
</tr>
<tr>
<td>NO3-45&quot;-W</td>
<td>1.35</td>
<td>0.80</td>
<td>2.24</td>
<td>1.59</td>
<td>1.47</td>
</tr>
<tr>
<td>NO3-45&quot;-E</td>
<td>1.17</td>
<td>0.76</td>
<td>1.92</td>
<td>1.63</td>
<td>0.82</td>
</tr>
<tr>
<td>NO3-60&quot;-W</td>
<td>1.30</td>
<td>0.89</td>
<td>2.43</td>
<td>1.54</td>
<td>-</td>
</tr>
<tr>
<td>NO3-60&quot;-E</td>
<td>1.46</td>
<td>0.72</td>
<td>2.46</td>
<td>1.51</td>
<td>1.39</td>
</tr>
<tr>
<td>average C.C.</td>
<td>1.31</td>
<td>0.76</td>
<td>2.20</td>
<td>1.58</td>
<td>1.47</td>
</tr>
<tr>
<td>(\sigma) (C.C.)</td>
<td>0.11</td>
<td>0.09</td>
<td>0.21</td>
<td>0.10</td>
<td>0.28</td>
</tr>
</tbody>
</table>

\[ \text{South - } H\alpha, H\beta, [\text{N II}], [\text{O III}], [\text{S II}] \]

\[ \text{average C.C. } 2.42, 1.45, 2.97, 1.39 \]

vii). Rotation

A noteworthy point in the reduction process is that a small rotation was found in the image after some positions were fitted polynomially, which changed the scaling factor of 1.2 (16' x 16' mapped into 800 x 800 pixels), to 1.21 in y, and 1.26 in x. In the
calculation of coordinate positions in the image offset from the WN star, the latter scaling factors and rotation correction terms were used, so that coordinate positioning in the images contributed very little to the calibration errors. To change from coordinates positions to pixel positions, the following equations were used:

$$x_2 = x_1 \text{ (WN or ref. star)} + dx + x'$$  \hspace{1cm} (2.1)

where, $dx =$ (offset in R.A. between the reference star and position in sec.) - converted to a difference in R.A. in pixels;

$$x' = dy \times (0.017)$$  \hspace{1cm} (2.2)

where 0.017 is the slope of the variation of R.A. with respect to change in $y$, caused by the rotation of about $1^\circ$ of the field, as in Fig. 2.1.

**Fig. 2.1**  R.A.(sec) vs. position

$$y = 1.6786 \mathrm{e}^{-3}x$$
Similarly,
\[ y_2 = y_1 \text{ (WN or ref. star)} + dy + y' \quad (2.3) \]
where, \( dy = \) (difference in Declination between reference star and offset position in arc sec.) - converted to a difference in Dec.in pixels; and
\[ y' = dx \times (0.016); \quad (2.4) \]
where 0.016 is the slope of the change in Declination with respect to a change in x, caused by the rotation, as in Fig. 2.2.

![Fig. 2.2 Declination (arc.sec) vs. position](image)

At this point, negative and bad pixels (especially those created by saturation of columns of photodiodes due to the bright stars) were either blanked or replaced with values interpolated from neighbouring pixels using the IRAF routine 'imedit'. Internal reflections of stars within the field reducing system produced bright and dark circular
patterns near the bright stars, which were also toned down to the background using 'imedit'. For the filters with a smaller bandwidth (~20 Å), as in Hα and [N II], there were significant radial variations in the transmission properties, especially at the edges of the images; although this problem was distinctly improved after using the new larger filters in front of the focal-reducing system, as was done with our observations.

Final calibrated images (in surface brightness units of $10^{-18}$ ergs cm$^{-2}$ sec$^{-1}$) of Hα, Hβ, [N II], [O III] and [S II] were obtained, as shown in the next chapter. These were then used for the scientific analysis in the chapters to follow. Ratio maps of some of these images, as in Fig.3.2 were also obtained by a pixel to corresponding pixel division between two images, using 'imdivide'. Scattered bright pixels, representing noise were found in the dark sky areas, especially in the ratio maps. We did not use smoothing algorithms for these in order to retain the high spatial resolution in our images. Results and interpretations concerning the final CCD images are presented in the following chapters.

II. 2. a. SPECTROPHOTOMETRIC OBSERVATIONS

Spectrophotometric observations of fourteen positions in the nebula were made in July and Sept. 1989, using the KPNO #2 36 inch telescope and the Intensified Reticon Scanner (IRS). The spectrophotometric positions were centered mainly on bright knots and filaments that had been observed in the Hα and [O III] surface brightness CCD images, and are depicted in Fig. 2.3. The seeing varied from about 2"-4". The IRS is used on the white spectrograph and the modified black guider. The IRS detector package consists of an ITT proximity-focused image tube with a 25 mm, S-20 photocathode, followed by a Varo microchannel plate coupled to a 2 x 936 dual reticon by a fiber optic window, although only 820 elements in the Reticon array are used.

Rectangular entrance apertures (dial setting 83.5) of size 35.6\" x 7.8\"
(separation - 61.2") were used, where the center of the west beam (aperture) was the position we were interested in. As this is an extended nebula though, most of the corresponding east apertures also lie along positions in the nebula and therefore also contained useful information. The positions observed, together with their west beam center coordinates and integration times are tabulated in Table 2.6. Grating no. 240, with 500 lines/mm, blazed at 5500 Å, and at a tilt of 16.35 was used to give a range of about 3500Å - 7200Å. During each night 2-3 standard stars of known energy distributions and He-Ne-Ar comparison line spectra (for wavelength fitting), quartz frames (for pixel to pixel variations), and dark frames were also obtained each night.
Table 2.6 Spectrophotometry Aperture Settings

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>NE1</td>
<td>20h 10 43.7</td>
<td>38° 17' 10&quot;</td>
<td>600s</td>
</tr>
<tr>
<td>O3spur</td>
<td>20h 10 26.14</td>
<td>38° 18' 27&quot;</td>
<td>1500s</td>
</tr>
<tr>
<td>NW1</td>
<td>20h 10 10.2</td>
<td>38° 15' 36&quot;</td>
<td>900s</td>
</tr>
<tr>
<td>W1</td>
<td>20h 10 4.9</td>
<td>38° 12' 57&quot;</td>
<td>900s</td>
</tr>
<tr>
<td>NW2</td>
<td>20h 10 9.6</td>
<td>38° 15' 30&quot;</td>
<td>900s</td>
</tr>
<tr>
<td>NE2</td>
<td>20h 10 52</td>
<td>38° 17' 18&quot;</td>
<td>600s</td>
</tr>
<tr>
<td>NO3</td>
<td>20h 10 44.5</td>
<td>38° 18' 42&quot;</td>
<td>3000s</td>
</tr>
<tr>
<td>NO3-15&quot;</td>
<td>20h 10 44.5</td>
<td>38° 18' 27&quot;</td>
<td>600s</td>
</tr>
<tr>
<td>NO3-30&quot;</td>
<td>20h 10 44.5</td>
<td>38° 18' 12&quot;</td>
<td>400s</td>
</tr>
<tr>
<td>NO3-45&quot;</td>
<td>20h 10 44.5</td>
<td>38° 17' 57&quot;</td>
<td>400s</td>
</tr>
<tr>
<td>NO3-60&quot;</td>
<td>20h 10 44.5</td>
<td>38° 17' 42&quot;</td>
<td>200s</td>
</tr>
<tr>
<td>SO3</td>
<td>20h 10 15.39</td>
<td>38° 6' 14&quot;</td>
<td>900s</td>
</tr>
<tr>
<td>S Knot-HN</td>
<td>20h 10 10.83</td>
<td>38° 6' 41&quot;</td>
<td>2400s</td>
</tr>
<tr>
<td>W5</td>
<td>20h 09 56.0</td>
<td>38° 13' 13&quot;</td>
<td>2400s</td>
</tr>
<tr>
<td>SW2</td>
<td>20h 09 55.3</td>
<td>38° 4' 54&quot;</td>
<td>600s</td>
</tr>
</tbody>
</table>

II.2.b SPECTROPHOTOMETRIC ANALYSIS

All the spectra were reduced at Rice University using the IRS Data reduction package 'NOAO/limred_lirs' in IRAF on the SUN 3/280. The data for each night was reduced separately, using the following steps. The IRAF commands are italicised:
i). **Wavelength Fitting**

Features in the reference (He-Ne-Ar) spectra were interactively identified and assigned standard wavelengths, using a mapping routine called 'Identify' and 'Reidentify'. *Identify* was used to determine a dispersion solution for the spectra. After trials with different functions and orders Chebyshev polynomials of order 12 were used for this dispersion solution, as these gave the best fit such that an r.m.s. of about 0.45 Å for the residuals were obtained. The fitting was good to about 2 Å at the center and about 4 Å at the edges of the spectra. Fig. 2.4 shows an example of a residuals vs. wavelength plot for one night. The wavelength dispersion relationships generated by running 'Identify' were used to map the spectra to the linearized coordinates with the task 'Dispcor' ('Dispersion-Correction').

ii). **Flatfitting**

The routine 'Flatfit' was used to add, fit and normalize the quartz spectra also taken during the observations to remove pixel-to-pixel variations. The best fit was obtained with Chebyshev polynomials of order 15 to give an rms residual of ~ 0.04 , after rejecting points greater than 2σ, as shown in Fig. 2.5 for one of the nights. A powerlaw correction was applied to the quartz data to correct for the effects of non-linearity of the instrument. The fitting function was then divided into the sum to produce normalized spectra from which the low frequency spatial response had been removed. The resultant normalized images were then divided into all other spectra to remove pixel-to-pixel variations.

iii). **Sensitivity Corrections**

The sensitivity information for each of the standard stars observed were computed. The sensitivity function is defined as the count rate (counts/sec/Å) observed
relative to the true flux of the observed star in ergs/cm²/sec/Å above the atmosphere:

\[
\text{Sensitivity} = \frac{\text{counts/sec/Å}}{\text{ergs/cm²/sec/Å}}
\]  \hspace{1cm} (2.5)

Extinction corrections were performed for the observed standard stars, using the I.R.S. standard star list from the KPNO standard extinction files. After fitting the data with Chebyshev polynomials of order 8 to give an rms of about 0.06 mag., while correcting for badpoints, specific bad star observations, weighting points, etc. (as shown in Fig. 2.6) a composite sensitivity curve is built from the observations so that all available wavelengths are represented. Each aperture yields a sensitivity spectrum which is used by the task `calibrate` to place all the observations onto a relative flux scale for each night.

iv) Sky Subtraction

The final results were then corrected for sky-contamination by subtracting the sky spectra. In ` nebular` mode both the west and east apertures of the telescope measured the object adjacently and was then offset to a specified sky position to measure the sky for the same amount of time. Finally, all the sequential results for a specific observation (ex. if 4 measurements were made of object/sky in sequence), were summed together to give better signal-to-noise ratio, and the final corrected spectra were obtained.

v). Spectral Line Measurements

Individual spectral line strengths were measured interactively using `mrjsplot`, by integrating the area under the line profiles directly, after specifying line center and continuum location, for strong unblended lines like Hγ, He II, Hβ, [O III] \( \lambda \lambda 4959,5007 \)
etc. For blended lines like the Hα λ6563 and [N II] λλ 6548,6584 triplet and the [S II] λλ 6716,6731 doublet, gaussian profiles were fit to individual lines to deconvolve the blend and get a more correct estimate. The continuum flux was estimated by measuring the mean value at the continuum level of nearby line-free regions. The statistical error for each emission-line was taken to be the product of the FWHM of the line and the RMS of the continuum. Sources of errors in the line intensities were due to uncertainty in line-fitting, setting of the continuum level, uncertainty in the instrumental sensitivity calibration, uncertainty in determining C(Hβ), the logarithmic reddening parameter and the wavelength dependence of the interstellar extinction. The spectral lines were normalized with respect to Hβ = 100.

The final spectrophotometric results are presented and analysed in the following chapters.
Figure 2.3. Spectrophotometric Slit Positions that were observed, marked on the CCD [O III] Surface Brightness Image.
Figure 2.4. Plot showing residues vs. wavelength, on determining a dispersion solution for the spectra.

Figure 2.5. Flat field fractional errors in fitting quartz spectra.
Figure 2.6. Sensitivity vs. wavelength, for observed standard stars. The lower plot shows sensitivity residuals vs. wavelengths.
III. RESULTS

III.1. OPTICAL EMISSION FROM NEBULAE

Surface brightness and ratio images of wind-blown shells or nebulae can convey a wealth of scientific information about the physical parameters and morphology of the nebula.

In this chapter we discuss the wide range of physical parameters and conditions that exist in NGC 6888. The CCD observations and the spectrophotometric data presented in the previous chapter are analysed to:

(1). Identify and isolate various scientifically interesting morphological features and trends as these are a result of physical processes that form and shape the nebula.

(2). Study the physical parameters (N_e and T_e, etc.) prevalent in the nebula.

(3). Determine the elemental abundances of He, N, O, S etc. in different regions of the nebula

(4). Map the ionic abundances to understand the ionization structure of the nebula.

These results allow us to quantify the nebular properties so as to understand the formation processes and the dominant physical mechanisms responsible for the wide range of existing conditions in NGC 6888.

III.2. CCD OBSERVATIONS: Morphology and Physical Structure

In this section we discuss the morphology, structure and other qualitative information imparted by our CCD emission-line imagery. The images all cover a 16' x 16' field mapped into 800 x 800 pixel arrays, i.e. 1.2' per pixel. Illustrations of the corrected and calibrated surface brightness images are presented in Figs. 3.1 a-e. Figs.
3.1 a and e show composite images in Hα and [O III], which were constituted by joining together the 'N' and 'S' fields of NGC 6888 taken during two different observing runs. Figs 3.1 b,c,d show separate 'N' and 'S' fields for the Hβ, [N II] and [S II] images.

It is apparent that very complex spatial structure exists in the surface brightness maps, on very small scales as well as large scales. The small scale local variations are obvious because of the high resolution of our imagery (∼ 2″).

In figs. 3.1a-e the images are displayed with an artificial colour code as shown below the images, with intensity or brightness increasing towards the right side of the colour scale. The individual images are labelled with the minimum and maximum pixel flux values that were used to display each of the images. All of the images are oriented with North to the top, and East to the left of the pictures.

III.2. a. Surface Brightness

In Hα, Fig. 3.1a, a limb-brightened, 'crescent-shaped' nebula is observed with the central WN star apparently offset from the center. The nebula has the appearance of an ellipse (discontinuous in the south-east), with the major axis of length ∼ 7.7 pc, assuming a distance of 1.45 Kpc (Wendker et al 1975). The major axis lies at a position angle of 35° passing through a point 3 " below the WN 6 star. The minor axis measures about 3.9 pc. The diffuse nebular material stretches in what appears to be a toroidal or donut-like fashion around the WN star along this ellipse. The nebula is delineated by a brighter shell encircling the diffuse ellipsoidal material. This shell has a thickness of about 0.01 pc, i.e. 1.4" (Johnson 1973), and appears to be discontinuous in the southeast (hereafter SE).

Bright, dense condensations (hereafter 'knots'), about 5-7" in length are found embedded in the nebulous material, concentrated in a few specific regions of the nebula, i.e. the north-east, northwest, west and south-west. Clusters of knots in each region
share common characteristics like average brightness, and orientation. The characteristics differ significantly from region to region though, and therefore we discuss these in more detail. The bright embedded knots also vary in position and relative brightness from one emission-line image to another. In the following section the relative positions and surface brightness of the knots in the different regions are compared for all the emission-line images, to quantify the differences.

III.2.a. i) The Knot Structures

Fig 3.1a shows the knot systems in Hα labelled as follows: in the northeast (A), northwest (B), west (C), southwest (D), south of the star (E), and just east of the star (F), but surprisingly none in the SE. We note that the SE region also lacks diffuse nebular emission. In the Hα image, A and D appear to be equally far away from the WN star, about 3.6 pc. along the major axis. B, C, E and F appear to be much closer to the star, but could actually be projection effects. The knots are embedded in less bright, diffuse but clumpy medium that goes to make up the nebula structure.

Fig. 3.2a shows an enlargement of an X by Y region of the top half of Hα, i.e. the NE and NW, to show the knot structure there in more detail. The knots appear as dense, irregular shaped (although most of them have length about 6''), structures that are significantly brighter than their intermediate surroundings. The brighter knots in the NE are labelled as A1, A2, A3 ..., and those in the NW are marked B1, B2, .... We note that the surface brightness is quite uniform from A to B in Hα. Fig. 3.3a shows a similar enlargement of the lower half of the Hα optical image. Again, the knots can be seen to be situated in specific clusters in the west, labelled as C1, C2, C3 ...; in the southwest marked as D1, D2,.. etc.; in a bright knot and arc structure to the south of the star that is labelled E1, and a couple of bright knots to the east of the star - labelled F1 and F2.
Fig. 3.2 b shows the same knots in the regions A and B, now marked in the [N II], [S II] and [O III] images. Unlike the Hα image, in the [N II] and [S II] images, the knots in A are much brighter than those in B. In contrast, for the [O III] image; the knots in B are much brighter than A.

To quantify the differences between the knots in more detail, the knot positions and surface brightness of specific knots were measured and correlated. The brightest pixel in each knot was located spatially, i.e. in terms of its x and y pixel coordinate location with a centroid routine. This routine also recorded the flux (in ergs cm\(^{-2}\) sec\(^{-1}\)) of the brightest pixel, the area of the contiguous pixels that go to make up each knot, and the average flux over this area for all the knots.

The twenty brightest knots in Hα for the NE and NW were recorded among the many such knots found, and are the knots that are labelled on the images in Fig. 3.2. Using these 20 knots in Hα as the reference knots, the centroids of the corresponding knots were located in the other emission-line images, and marked with the same label as in the Hα image. The Hα image was used as the standard image as it has bright knots in all the regions referred to, unlike the other images that are more inhomogeneous. Any knot in these images that had a centroid offset by more than 3 or 4 pixels from the Hα image was considered to be a different knot and was discarded from our analysis.

The brightness corresponding to the centroids, i.e. the maximum brightness of the knots in units of ergs cm\(^{-2}\) sec\(^{-1}\) were then plotted as a function of the 'x' pixel coordinate, in Fig. 3.4a. The 'x' pixel coordinate and not the distance from the star was preferentially chosen as the abscissa, as plotting along the 'x' coordinate separates out the knots in A and B, in a manner similar to what is visually obvious from Fig. 3.2.

Fig. 3.4a shows that the knots in region B for all the images are closely grouped together, and the difference between the [O III] cluster and the Hα and [N II] groups (which lie at the same flux level) is only about 6 \times 10^{-15} \text{ ergs cm}^{-2} \text{ sec}^{-1}. On the
other hand, there is a big variation in fluxes for the knots in the region marked 'A'. The 'A' knots in [N II] are brighter than those in Hα by about 1 x 10^{-14} ergs cm^{-2} sec^{-1}, whereas the 'A' knots in [O III] are fainter than that in Hα by almost the same amount. The knots in [S II] are much fainter than any of the other images, but in a manner similar to the [N II] image, the knots in A are brighter than the knots in B.

Fig. 3.4b is a similar plot showing the centroid or maximum fluxes of the knots in the south half (i.e. C, D, E and F) of Hα compared to the other images, in this case as a function of y (in pixels). The knots in the South for the images is shown in Fig. 3.3.b. Again, we see that the knots in C, and F for all the images have a comparable surface brightness, on the contrary there is a large difference in the brightness of the knots in D (southwest), and in the S knot (E). The situation in the SW (D) is remarkably similar to what was seen in Fig. 3.4a in the NE (A), in terms of surface brightness, and also variations between images. The 'D' knots in [N II] are again brighter than the 'D' knots in Hα by about a factor of 2, and in comparison [O III] is lower than Hα by about the same amount.

From the previous discussion Figs.3.4 a and b points to physical similarities in the knots in A and D in terms of surface brightness in all the images. The ratio of [N II]/Hα and [O III]/Hα brightness in both regions is about the same. This an important fact to note, as these two regions are equidistant and symmetrical about the WN star. These two results together imply that these two positions may have been created by the same physical process.

III.2.a. ii). Other Outstanding Features

Besides these knots, Figs. 3.2 and 3.3 a,b also show a few more interesting features. One of these are the jets marked A21 and A22 in Hα, [N II] and [S II]. These are protrusions that seem to have broken through the confines of the ejecta limits and
project out into the ambient medium. In the [O III] image, a bubble appears to have broken through between the area defined by the two jet-like structures A21 and A22. A few other similar 'protrusions' are found in the South and NE, but A21 and A22 are the most prominent ones.

III.2.b. **THE [O III] IMAGE**

In comparison to Hα, [N II] and [S II], the nebula appears visually significantly different in the [O III] (Fig. 3.1e) surface brightness image, both in large-scale morphological structure or appearance as well as in the structures of the knots, as discussed earlier. The [O III] emission can be divided into two zones: (1) The inner nebula, (2) Outer structure.

1. **The Inner Nebula**

The inner toroidal nebular emission (hereafter the 'inner shell') is morphologically similar and coaxial to the emission observed in the other images; although the positions of the knots vary, as we have shown before, in NE (A) and SW (D) mainly. In F the ridge leads up to a well defined knot (E) and a strong arc of emission. We note here that the knot E is extremely bright in [O III] and Hα, although the centroids of this knot in the two images is offset by a couple of pixels. These positions were in our list of spectroscopic apertures as mentioned in the succeeding sections and are referred to as the 'SO3' and 'SHN' knots respectively. In the case of Hα although 'E' is visible as an extremely bright knot, the arc is not well defined. Another structure that is significantly different in the [O III] image is the arc A16 which is much brighter and extended in [O III]. A16 extends into long, bright arcs of emission to the NE. In Hα this feature is only noted as a bright knot. Fig. 3.1e also shows a bright arc or 'rim' like feature directly to the east of the bright star in the north of our field, which we have named the 'O3Spur'. This was also included in our spectroscopic positions, as it is an
unusual feature both in terms of position and morphology.

2. The 'Outer' Region

Bright [O III] filaments, arcs and bubbles stretch out into the ambient medium, mainly in the NW and SE, constituting the 'Outer Part' of [O III] that is not visible in any of the other images (hereafter 'Outer Bubble'). This bubble-type emission in the [O III] is almost antisymmetric to the main body of the Hα emission i.e. the [O III] bubble structure stretches out along the minor axis of the nebula (at a position angle of 55°) up to about 8 pc, beyond the diffuse emission common to all the images which extends up to only about 5 pc along the minor axis. In the NW quadrant, as Fig. 3.1c shows, the emission resembles well defined 'bubbles'. The bubbles are spherical, and resemble layers of onion skin, i.e., spherical shells moving out into a homogeneous, less dense medium. The extended emission in the SE is more reminiscent of a 'lattice' or matrix-like structure. A notable point though, is that a bright [O III] emission rim is seen predominantly on the leading edge of regions in which all the other lines appear, almost encircling the whole inner ellipsoidal area. This feature is brought out more markedly and discussed in detail in the ratio maps (ex. [O III]/Hα).

The nebula thus appears to be bipolar, with H I, [N II] and [S II] emission along an axis perpendicular to the majority of the filamentary [O III] emission. The bipolar nature of the emission is reminiscent of planetary nebulae like the dumbbell nebula. This is discussed in later chapters.

III.3. RATIO MAPS

The ratio maps have a very different appearance than the surface brightness maps. From eqn. 3.2 we see that a ratio of the emissivities of two forbidden lines is a function of the ionic densities of the two ions, and Te and Ne. The dependence of the
ratio of the emissivities on these three parameters depend on which atomic levels the lines originate from.

Relative locations of ions like [N II]/[S II] etc. reflect different excitation mechanisms, as these ions have very different ionization potentials, shown in Table 3.1. Ratio maps therefore map the ionization structure of the nebula in one emission line in comparison to another. Our observations are actually an integration of zones with different ionization levels along the line of sight.

**TABLE 3.1 IONIZATION POTENTIALS (ev.)**

<table>
<thead>
<tr>
<th>ATOM</th>
<th>I</th>
<th>II</th>
<th>III</th>
</tr>
</thead>
<tbody>
<tr>
<td>H</td>
<td>13.6</td>
<td></td>
<td></td>
</tr>
<tr>
<td>He</td>
<td>24.6</td>
<td>54.4</td>
<td></td>
</tr>
<tr>
<td>N</td>
<td>14.5</td>
<td>29.6</td>
<td>47.4</td>
</tr>
<tr>
<td>O</td>
<td>13.6</td>
<td>35.1</td>
<td>54.9</td>
</tr>
<tr>
<td>S</td>
<td>10.5</td>
<td>23.4</td>
<td>35.0</td>
</tr>
</tbody>
</table>

In the following section we discuss the ratio maps as shown in Fig. 3.5 a-d, and their scientific significance:

**I. Hα / Hβ Ratio Image (Fig. 3.5.a)**

Hα / Hβ shows small reddening variations over the nebula. From eqn. 3.1 the ratio of j(Hα) to j(Hβ) are functions of T_e and N_e. At a specified T_e and N_e, the ratio depends only on atomic data; and at a value of T_e = 10,000 °K and N_e = 100 cm^{-3}, the Balmer decrement is equal to 2.86.

Fig. 3.6a shows the Balmer decrement value of the same reference knots as in
the Hα reference image plotted against the 'x' coordinate in a manner similar to Fig. 3.4.a. This shows reddening to be uniform in all but the NE region. The NE shows a higher Balmer decrement ~ 5.8 - 7, as compared to the rest of the nebula where it is about 5.5 to 6. Similarly, Fig. 3.6.b plots the Hα / Hβ ratio of the E, W and SW knots vs. the 'y' coordinate, analogous to Fig. 3.4b. The reddening is more uniform in the southern half of the nebula, and has a value of 5.8 ± 0.5 on average. The range in Hα / Hβ is comparable to that found in earlier spectrophotometric observations (Kwitter 1981). Variations in reddening is mainly due to statistics in the measurement and analysis techniques. A lack of significant variation in reddening just exterior to the nebular region is indicative of a lack of foreground reddening. The non-uniformity in the NE indicates some clumpiness or internal dust in that area.

III.3.b. [O III] / Hα (Fig. 3.5.b)

This is one of the most informative ratio maps to depict the nebula in, as it shows the two complementary ionization structures, and morphologies along the two axes. This ratio image simultaneously gives an idea of the competing physical processes forming and shaping the nebula, i.e. this ratio outlines the diffuse nebular emission area, ('Inner shell') common to all the emission-line images, and the outer bubbles and filaments which is visible only in the [O III] image. The division of the nebula into two distinct morphological and physical zones is discussed in a later section.

III.3.b.1. The 'Rim'

A bright [O III] boundary, delineating the diffuse internal nebular region, stretches around almost all of the nebula. This boundary resembles a bright 'rim' all around the inner material, and stretches outside the extent of the Hα emission region. The high [O III]/Hα defines the leading edge of the nebula with the value of the ratio at
around 2-4 along the rim. At certain positions however, (for example, at positions marked A21 and A22 in the NE and D1 in the SW), the strong [O III] wraps just outside the Hα and [N II] emitting material. These features were noted previously in our discussion of the Hα surface brightness features, and were compared to 'jet-like' protrusions. An [O III] bubble appears to burst out of the confines marked by the A21 and A22 edges. As noted before, the [O III] shocked shell structure is discontinuous in the SE region.

III.3.b.ii) Bubbles in the NW

Strong [O III] filaments and bubbles break out through the boundary defined by the Hα extension, and protrude out into the ISM, particularly in the NW. The [O III]/Hα ratio in these bubbles is about 2-3. This 'bubble' system is not observed in any of the other line-images. The bubbles in this region are very well defined and form a complex but symmetric system. There are several spherical bubbles, of different radii, reminiscent of an onion skin cross section. The bubbles appear to be filaments that are being viewed edge-on. These are marked as B1, B2, B3 and B4 in Fig. 3.5b. The larger bubble, i.e. B4 stretches out along the minor axis to a distance of around 3.6 pc. from the center and this is close to the extent of the Hα emission along the major axis. The brighter filaments in the NW and SE portray strong [O III] emission compared to Hα ([O III]/Hα ~ 2-3), whereas in comparison the darker inner ejecta region indicate that Hα is stronger than [O III] in the inner ejecta region (Ratio = 0.1-0.6). These far-stretching bubbles in the NW imply that a fast wind is blowing through vacuum or low density ambient medium in this area. The low emission measure in the region interior to the bubble cavities suggests low density medium in this region. This is of significance in our knowledge of the formation of the nebula, and will be discussed in the next chapter.
III.3.b.iii) Lattice in the SE

The [O III]/Hα image presents a totally different shape and morphology in the SE quadrant. The [O III] outer rim is discontinuous in this region. Bright [O III]/Hα is found as filaments interweaved in a 'lattice' like or honeycomb structure. The former is the only representation of [O III] emission in this quadrant, as no knots are visible in this area. This filamentary structure suggests a wind of higher density propagating through a low density medium, and suffering from some instabilities, possibly Rayleigh-Taylor instabilities during the interaction. These instabilities appear as broken filamentary structures. These structures appear to be 'face-on' filaments in contrast to the 'bubbles' in the NW.

III.2.b.iv) NE and SW

Unlike NW and SE which are dominated by [O III] emission, NE and SW are dominated by the Hα emission. As noted before, the [O III] emission extends outside the range of the Hα image, and is visible as a bright encircling rim. Another unusual morphological feature in the NE is the 'spur' marked in Fig. 3.5.b. This structure is a bright and distinct arc that leads off into the bubble in the NE marked by A21. This spur has a high [O III]/Hα of around 3; actually Hα is almost absent in this position. This feature is specific to the [O III] image, and is not identifiable in any of the other line images.

The most remarkable feature to note in the south is the extremely bright knot marked 'E1' in Figure 3.1.e. This feature is bright in Hα as well. But in the [O III] image, this knot trails off into a distinct arc that is not so well defined in the Hα image.
III.3.b.v). The Knots

In the way similar to our analysis of the knots in the other line images, Fig. 3.6a and b shows the ratio of the same bright knots in the north and south half of the nebula respectively. The ratio maintains a uniform average value of around 0.2-0.3 in the NE(A), W(C), SW (D), and E(F). The exception is in the NW (B), where [O III] is comparatively brighter and the ratio is about 0.6.

This gradient in the [O III] / Hα ratio over the nebula remains valid even after dereddening the images, and is therefore not due to the higher reddening observed in the NE. Although both [O III] and Hα exists in the diffuse region and also as the bright embedded knots, the knots do not exactly combine, and are sometimes offset by 1-3 pixels. Also, some of the knots in the NE and SW present in Hα image are not present in the [O III] image at all, whereas in NW and W most of the knots exist, and the centroids are located at almost the same position.

The analysis of these regions together again suggests that NW and SE that are located diametrically opposite along the projected major axis are very different morphologically compared to NE and SW. This indicates that the 2 axes are physically different.

III.3.c. [N II] / Hα Ratio Image (Fig.3.5.c)

[N II]/Hα brings out the variations in the bright ellipsoidal or toroidal part of the nebula, from region to region. Morphologically, [N II] is remarkably similar to the Hα image. An analysis of the knots in all the regions is presented in Fig. 3.6 a and b as in the other cases. This ratio is found to be much stronger in NE (~2) and SW (~1.5) than in NW (~0.45) and W (~ 0.4). As NW and W are located much closer to the star, both in terms of apparent projected distance and real distance (discussed in the geometric model presented in the next chapter), this variation could be due to ionization difference, as a
result of dilution of ionizing photons with distance. This idea was supported by Parker (1978). On the other hand, the [N II]/ Hα variation could be due to an abundance variation between the two regions. Surprisingly, the knot marked E1 directly to the East of the WN star, that was found to be extremely bright in both Hα and [O III], is much fainter in [N II]. The [N II]/ Hα ratio in this knot is found to be only 0.2. This is also probably a result of the geometry of the nebula, as this knot may be much closer to the star than even some of the knots in the west (ex. C5) that appear to be closer. If that is the case, then the knot would be very highly ionized, and explain the low [N II] / Hα ratio, as the N would be in higher ionization stages.

III.3.d. [S II]/ [N II] Ratio Image (Fig. 3.5.d)

This ratio marks the location of ionization fronts plowing into dense material, as the H+ zone is ionization bounded, but the S+ zone is not. Sulphur remains singly ionized only in very dense regions where it is shielded from ionizing UV photons. Regions of enhanced [S II]/Hα mark the locations of ionization fronts plowing into dense material. A comparison of the knots over the nebula is shown in Fig. 3.6a and b again. The knots are much brighter in NE (~0.3) and SW (0.2) , and barely visible in the W and NW (~0.1). This is probably due to incomplete ionization in the NE and SW as noted before for the [N II]/ Hα image.

[S II]/Hα falls off over 4-5 pixels at the edges. In this object, the shell thickness is given to be 0.01pc (Johnson 1973 ) ~ 3 x 10^{16} cm. Dyson and Williams (1980) give the thickness of an H II region to be ~ 0.48 n_{0}^{-1} pc, i.e. 56 n_{0}^{-1} pixels at the distance of 1.45 Kpc. For n_{0} = 10 cm^{-3}, as calculated in a later section for the value of the ambient density, therefore the recombination region is about 5.6 pix, or 0.05 pc. in size. In this case therefore, the [S II]/ Hα does not fall off as abruptly as the homogeneous case indicates.
III.4. **SPECTROPHOTOMETRIC OBSERVATIONS**

Our imagery results were complemented by the spectrophotometric results obtained at KPNO, as discussed in the last chapter. The final calibrated spectra are presented in Fig. 3.7. The spectra are offset such that all of them are scaled to the first (lowest) spectra, in each set of plots. The wavelength range extends from 3500 Å to about 6900 Å. The spectra are also labelled with the corresponding position on the right. These positions are the same as the ones mentioned in Table 2.5. Most of the positions shown are the west aperture positions (marked W), as the W aperture was actually centered on features of interest. A few of the East positions were also included in the analysis (marked -E); these were the positions that were actually located interior to the nebular region, and therefore have good signal to noise spectra as well.

The strongest lines observed are the H I recombination lines Hα, Hβ, Hγ and Hδ and He I λ5876, 6678; as well as the forbidden lines of [O III] λλ4959,5007, [N II] λλ6548,6583 in most of the spectra. Weaker lines found in many of the spectra are the forbidden lines of [S II] λλ6716,6731, and [O II] λλ3727,3729.

As noted in the last section, physical conditions and the ionization structure varies considerably over the nebula. The inner diffuse nebular zone, appears to have Hα and [N II] λλ6548,6583 lines of strength higher or comparable to that of the [O III] λλ4959,5007 lines. This is true for the positions in the NE, the NW, the W and the SW. On the contrary, in the bubble region [O III] λλ4959, 5007 are much stronger than [N II] and the H I lines. This is true in particular for 'NO3' and 'O3Spur', both of which are located directly on the filamentary features, and hence outside the Hα recombination zone. Fig. 3.8 shows a variation of N II [6584] with observed (projected) distance from the WR star. This plot is similar to that of Parker (1978), and shows that ionization is a smoothly varying function of distance from the WR star.
FIGURE 3.8. I[6584] vs. distance from WR star, for NGC 6888

FIGURE 3.9. I[5007] vs. I[6583] for NGC 6888 positions
Fig. 3.9 further shows that the trends of I[5007] and I[6584] are in opposite directions. This indicates that the variations in line intensities throughout the nebula is likely to be a result of changing ionization, and not due to a change in abundances. Note, the high value of [O III] in Fig. 3.9 corresponds to the O3Spur position, and NO3-W which has an even higher value of λ5007 lies outside the scale in the plot.

III.4.a. Reddening Corrections

The spectral lines that had been normalized to Hβ = 100, were then corrected for reddening using the extinction curve and values of f(λ) from Seaton (1979). The reddening function f(λ) is normalized such that f(Hβ) = 0. Interstellar extinction makes the observed intensity ratio of two nebular emission lines F(λ1) / F(λ2) differ from their ratio as emitted in the nebula I(λ1) / I(λ2) in the following manner:

$$\frac{I(\lambda)}{I(H\beta)} = \frac{F(\lambda)}{F(H\beta)} \times 10^{C(H\beta) f(\lambda)}$$  \hspace{1cm} (3.4)

The value of C(Hβ) is calculated by comparing the observed I(Hα) / I(Hβ) ratio to the theoretical Balmer decrement. C(Hβ) is the logarithmic extinction at Hβ, defined as:

$$C(H\beta) = \log I(H\beta) - \log F(H\beta)$$  \hspace{1cm} (3.5)

The theoretical Balmer decrement is adopted to be 2.86 (Brocklehurst, 1971), which has this theoretical value at T_e = 10,000 °K and N_e = 100 cm⁻³, under Case B recombination conditions. Case A (Osterbrock, 1974) assumes that all H I line photons emitted in the nebula escape without absorption and therefore without causing further upward transitions. Case A is a good approximation for gaseous nebulae that are optically thin in all H I absorption lines. Case B is true for nebulae that have large optical depths in the Lyman resonance lines of H I. In these cases a Lyman-line photon is converted (if n ≥ 3) into lower series photons plus either Lα or two-continuum photons. NGC 6888 lies in
between both the cases, as parts of the nebula, i.e. the toroidal-shaped inner ejecta is radiation bounded; whereas other parts of it like the escaping [O III] bubbles are material bounded. For a $T_e = 10,000\, ^\circ K$ and $N_e = 100 \, \text{cm}^{-3}$, Case A and B both give $j_{\text{H}\alpha}/j_{\text{H}\beta} = 2.86$. Therefore our choice of Case A or B does not make a difference here. Also for $T_e = 10,000\, ^\circ K$ and $N_e = 1000 \, \text{cm}^{-3}$, Case B gives a Balmer decrement of 2.85. Therefore, although in a later section (III.3.c) diagnostics show densities ranging from $N_e = 10 \, \text{cm}^{-3}$ to $N_e = 800 \, \text{cm}^{-3}$ in the nebula, the prevailing spread of densities does not significantly change the value of the applicable theoretical Balmer decrement. Utilization of this value of the Balmer decrement also keeps our results consistent with earlier literature (Parker 1978). Individual values of $C(\text{H}\beta)$ were derived for each position, and are recorded at the bottom of Table 3.2 for each observation. $\text{H}\alpha$ and $\text{H}\beta$ were well measured (with errors of < 5%) for most positions, and therefore this ratio was accurately determined in almost all the cases. The values range from $C(\text{H}\beta) = 0.52$ ($\sim E(\text{B-V}) = 0.36 \, \text{mag.}$), to $C(\text{H}\beta) = 1.16$ ($\sim E(\text{B-V}) = 0.79 \, \text{mag.}$). Parker (1978) found a variation in $E(\text{B-V})$ of 0.29 mag. to 1.19 mag. Wendker et al. (1975) proposed a value of $E(\text{B-V}) = 0.54 \, \text{mag.}$ on the basis of the absorption for the Wolf-Rayet star. Our values agree reasonably well with these results.

III.4.b Emission-Line Data

The reddening corrected line fluxes for the nebular positions observed are presented in Table 3.2. The values of $C(\text{H}\beta)$ used for each position are also listed at the bottom of each column. From left to right, the columns list the line wavelengths in angstroms ($\AA$), the line identifications, the reddening corrected line intensities relative to $\text{H}\beta = 100$, and the estimated errors in the observed line strengths relative to $\text{H}\beta$ (rms standard deviation, $\sigma$) for each position. The error codes are: (a) $\sigma \leq 10 \%$, (b) $10 \% < \sigma \leq 20 \%$, (c) $20 \% < \sigma \leq 30 \%$ (d) $30 \% < \sigma \leq 50 \%$. Sources of errors considered in
Table 3.2. Dereddened Line Fluxes (x $10^{-14}$ ergs cm$^{-2}$ s$^{-1}$)

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Table 3.2. Dereddened Line Fluxes (x 10^{-14} ergs cm^{-2} s^{-1})

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Table 3.2. Dereddened Line Fluxes (x 10^{-14} ergs cm^{-2} s^{-1})

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measuring the line intensities were uncertainties in the line-profile fitting procedure and in
determination of the continuum level, uncertainty in determination of C(Hβ) and the
wavelength dependence of the interstellar extinction, etc. Some of the measured lines
were at the 2σ level; but were important for diagnostics, etc. (ex. [O III] λ4363). These
lines were fitted with 'forced' gaussians, where either the centers or the FWHM's were
fixed. Lines measured in this way have a 'g' next to them in Table 3.2.

III.4.c Diagnostics

Both the [O III] and [N II] diagnostic lines are quite strong in 6-9 of the
nebular positions, therefore it was possible to calculate separate [O III] and [N II]
electron temperatures corresponding to a high-ionization shocked zone where O+2 is
located, and a low-ionization zone where N+ is located.

The $T_e$ and $N_e$ were calculated using a 5-level atom population fortran
program, FIVEL, (DeRobertis, Dufour and Hunt 1987) based on the atomic data
compilation of Mendoza (1983). This interactive program determines the physical
conditions in a nebula given the appropriate emission line intensity ratio and either the
electron density, for $T_e$ determination, or vice versa. Further descriptions of the
underlying physics and description of the program is given in the mentioned reference.
The $T_e$ and $N_e$'s calculated for the positions are presented in Table 3.3.

For some of the positions, $T_e$ could not be calculated due to an insignificant [O III]
$\lambda$4363 (~10 positions), or the [N II] $\lambda$5755 line (8 positions); these positions just have
blanks beside them. In an analogous manner, for eight of the positions $N_e$ was
impossible to determine because of the low [S II] $\lambda\lambda$6716,6731 lines. The errors were on
the order of 20-40% for the $T_e$'s, and on the order of 15-25 % for the values of $N_e$'s.
Table 3.3 shows significant variations between the [N II] and the [O III] $T_e$'s. The [N II]
$T_e$ averaged over 11 of the observed points was 8000 ± 2400 °K, whereas the [O III] $T_e$
averaged over the NW, W, and SW (5 positions) was $\sim 13,000 \pm 4000$ °K. Large variations, from 13,000 °K in the West to 55,000 °K for the shocked NO3 position is found in the [O III] $T_e$ over the nebula, and this variation is discussed further in the next paragraph. The errors are based on the continuum flux level calculated in that region for the $\lambda$5755, $\lambda$4363 lines mainly, and to a much smaller extent on the $\lambda\lambda$6548, 6584 and $\lambda\lambda$4959, 5007 lines. The [N II] $\lambda$5755 and [O III] $\lambda$4363 lines were measured only at a 2-4 $\sigma$ statistical significance.

<table>
<thead>
<tr>
<th></th>
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</tr>
</thead>
<tbody>
<tr>
<td>NE1 - W</td>
<td>9780±1500</td>
<td>29,100±10000</td>
<td>600</td>
</tr>
<tr>
<td>NE1 - E</td>
<td>-</td>
<td>-</td>
<td>10</td>
</tr>
<tr>
<td>NE2 - W</td>
<td>7300±3200</td>
<td>23,800±9000</td>
<td>300</td>
</tr>
<tr>
<td>O3spur - E</td>
<td>-</td>
<td>-</td>
<td>1000</td>
</tr>
<tr>
<td>NW1 - W</td>
<td>9980±1600</td>
<td>16,500±1500</td>
<td>600</td>
</tr>
<tr>
<td>NW1 - E</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>NW2 - W</td>
<td>9500±1900</td>
<td>11,900±1600</td>
<td>-</td>
</tr>
<tr>
<td>W1 - W</td>
<td>7600±1000</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>NO3 - W</td>
<td>-</td>
<td>55,000±2000</td>
<td>-</td>
</tr>
<tr>
<td>NO3 -15&quot;-W</td>
<td>8200±1200</td>
<td>19,000±2000</td>
<td>600</td>
</tr>
<tr>
<td>NO3 -30&quot;-W</td>
<td>6700±1100</td>
<td>-</td>
<td>600</td>
</tr>
<tr>
<td>NO3 -45&quot;-W</td>
<td>9400±1000</td>
<td>16,000±2000</td>
<td>10</td>
</tr>
<tr>
<td>NO3 -45&quot;-E</td>
<td>-</td>
<td>-</td>
<td>1000</td>
</tr>
<tr>
<td>NO3 -60&quot;-W</td>
<td>7050±1500</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>NO3 -60&quot;-E</td>
<td>6500</td>
<td>-</td>
<td>200</td>
</tr>
<tr>
<td>SO3 - W</td>
<td>8000±700</td>
<td>12,000±1500</td>
<td>10</td>
</tr>
<tr>
<td>SW2 - W</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Sknot-HN</td>
<td>11,150±1300</td>
<td>14,000±1500</td>
<td>800</td>
</tr>
<tr>
<td>W5 - W</td>
<td>-</td>
<td>13,900</td>
<td>50</td>
</tr>
<tr>
<td>O3 Sknot</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>
NO3-W shows an unusually high value of $T_e$. The value of $T_e$ at this position is 55,000 °K ± 15,000 °K. NO3 as shown in Fig. 3.8, lies just outside the bubble feature marked A21 in Fig. 3.1.e; which is the rim of the bubble found in the NE top part of the O III image. In the Hα image this feature is close to A21, which is noted only as a jet-like protrusion into the ISM, but the bubble rim is not apparent. Similarly, in the [N II] image this position is noted as a jet and not a bubble. Therefore visually it appears that this feature arises in the outer shocked zone, and has mainly [O III] emission. This assumption is validated by the spectra of NO3, presented earlier in Fig. 3.7. The spectra shows very strong [O III] and much weaker [N II] and Hα lines. A zoom showing the $\lambda\lambda4340+4363$ lines and the Hβ $\lambda4363$, [O III] $\lambda\lambda4959,5007$ lines are shown in Fig. 3.10. This figure shows very weak Hβ. The Hγ $\lambda4340$ line is mixed with the [O III] $\lambda4363$ line in such a way that it was not possible to deconvolute them. Gaussians were fit to the four lines separately, i.e. the 4340+ 4363 line combination as one line, Hβ, and the [O III] $\lambda\lambda4959, 5007$ lines. [O III] $\lambda4363$ can be separated from the Hγ contribution, by using the fact that at a $T_e \sim 10,000$, and $N_e \sim 100$, the Balmer ratio $j_{H\gamma}/j_{H\beta} = 0.47$ (Osterbrock 1974). Subtracting this fraction from the reddening corrected combined line intensity gives a value of $I\lambda4363 = 178$, and the $(I4959 + I5007) / I4363$ ratio $\sim 14.8$. This ratio implies an [OIII] $T_e \sim 55,000°K$. This suggests that this feature is located in the outer thin, hot, shocked [O III] shell.

III.4.d. Zone separation

The preceding discussion about NO3, and comparisons to the $T_e$'s obtained for the other positions, indicates that a large variation in [O III] $T_e$'s is observed. Besides the exceptional NO3-W 55,000 °K feature, the observed [O III] $T_e$'s in the NE region (NE1-W and E, NE2, NO3-15) are much higher $\sim 25000°K$, in comparison to the [O III]
$T_e$ determined from other regions, which is about 13,000 °K. This indicates that the observed [O III] $T_e$ is an integrated effect along the line-of-sight, and therefore has a contribution from the hotter shocked outer bubble, as well as the cooler inner regions and knots. The different values in [O III] $T_e$'s indicate that different fractions of [O III] emitting material contribute. The fraction of hotter (shocked zone ~ 55,000°K) or cooler (inner region - [N II] $T_e$ ~ 8000 °K) material that contributes to the observed $T_e$ in each position depends on the location and geometry of the specific observed position.

To correct the observed [O III] $T_e$ for this line-of-sight mixing, the contribution of the shocked region to the observed $T_e$ was separated from that of the inner nebula. This was done from the estimates of the ratio of the surface brightness of the knots to the surface brightness of the surrounding bubble at any given region, from the $\lambda 5007$ CCD images. The knots were taken to be features representative of the inner emission region. The surface brightness in $\lambda 5007$ was assumed to be a linear combination of emission from the knots and from the surrounding bubble in the following way:

$$I_{(5007)}^{\text{obs}} = k \times I_{(5007)}^{\text{knot}} + b \times I_{(5007)}^{\text{bubble}}$$  \hspace{1cm} (3.6)

where $k$ and $b$ are the fractional contributions of the knots and bubble regions respectively to the total emission. i.e. In case of a feature that has no bubble contribution $k$ would be equal to 1, and $b = 0$. As $I(5007)$ is proportional to $j(5007)$, where $j(5007)$ is the emissivity, (3.5) can be rewritten as:

$$j_{(5007)}^{\text{obs}} = k \times j_{(5007)}^{\text{knot}} + b \times j_{(5007)}^{\text{bubble}}$$  \hspace{1cm} (3.7)

'k' and 'b' were determined by measuring a section of the brightest part of some of the knots for $k$, and a section of the same area in the diffuse nebular area interspersed between the knots for $b$. Using the measured values of $k / b$ for each region, i.e. NE, NW, W, and SW and from the fact that $k + b = 1$, values of $k$ and $b$ were obtained for each position. Solving (3.6) for the 3 positions listed below as simultaneous equations, values of $j(5007)$ corresponding to the knots and bubbles were obtained, that lead directly
to the values of $T_e$ for the knots and bubbles at a specified $N_e = 400 \text{ cm}^{-3}$. For the different regions, from the ratios of average surface brightness for each region different values of $k$ and $b$ were obtained, and these in turn gave values of $T_e$ for the knots and bubbles, as shown in Table 3.4:

**TABLE 3.4 $T_e$ knot and $T_e$ bubble**

<table>
<thead>
<tr>
<th>POSITION</th>
<th>$k$</th>
<th>$b$</th>
<th>$T_{e\text{ knot}}$</th>
<th>$T_{e\text{ bubble}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>NE</td>
<td>0.64</td>
<td>0.36</td>
<td>11,000</td>
<td>50,000</td>
</tr>
<tr>
<td>NW</td>
<td>0.86</td>
<td>0.14</td>
<td>6500</td>
<td>50,000</td>
</tr>
<tr>
<td>W</td>
<td>0.78</td>
<td>0.22</td>
<td>11,000</td>
<td>50,000</td>
</tr>
</tbody>
</table>

Similar calculations using the observed knot/bubble ratios and observed [O III] $T_e$ for each of the regions yields an average of 50,000 °K for the shocked bubble $T_e$. The individual bubble position $T_e$ values are also given in Table 3.4. The average [O III] $T_e$ for the knots from Table 3.4 is calculated to be $\sim 9000 \text{ °K}$, similar to the [N II] $T_e$ derived previously. This is an expected result as the [N II] emission originates only in the inner nebular region, and therefore is characteristic of the knot temperatures. The value of $T_e \sim 50,000 \text{ °K}$ for the bubble is also consistent with the result we had obtained for our NO3-W feature, which has no knot contribution, (i.e. $k = 0$) and is believed to be originating in the shocked outer shell.

There are also large variations between the $N_e$'s determined for the various positions; variations extending from about 10 cm$^{-3}$ to 800 cm$^{-3}$. This indicates the existence of substantial temperature and density fluctuations in this nebula.
Fig. 3.11 shows a diagnostic plot for two of the positions, NE1 and NW1. The plot consists of the $T_e$ sensitive [N II] 6548 + 6583/5755 and the [O III] 5007+4959/4363 ratios (before the filtering out of knot vs. bubble contributions), and the $N_e$ sensitive [SII] 6716/6731 ratio, all plotted as a function of $T_e$ and $N_e$. This plot illustrates the fluctuations in $T_e$ and $N_e$ over the nebula. The preceding discussion suggests that the nebula can be divided into two zones: (1) A high-ionization, high $T_e$, low $N_e$, [O III] zone, i.e. the outer shocked bubble region, (2) A low-ionization, low $T_e$, high $N_e$, H$\alpha$ zone, i.e. the inner recombination region which includes the ellipsoidal nebular region and the knots. For the [O III] zone we adopt a $T_e \sim 50,000$ K, and for the H$\alpha$ zone, a $T_e$
~ 8000 °K. We used an average $N_e$ of about 400 cm$^{-3}$ for all the positions, as the line emissivities are quite insensitive to $N_e$, besides the [S II] lines. It is probable that these two zones are the results of two different physical processes, where it looks like the [OIII] zone is the hot, shocked region, and the Hα zone is actually the inner recombination zone. These surmises are substantiated in the next chapter.

Note, the high value of [O III] correspond to the O3 Spur position.

3.4.d Ionic Abundances

The ionic abundances relative to H$^+$ were computed using the dereddened line intensities $I(\lambda) / I(H\beta)$ in the following manner:

$$\frac{N(X^i)}{N(H^+)} = \frac{I(\lambda)}{I(H\beta)} \times \frac{j(H\beta)}{j(\lambda)} \quad (3.8)$$

Where $j(\lambda)$ is the theoretically determined line emissivity per ion, and is given by eqn. 3.2. The effective recombination emission coefficients, $\alpha$ (from eqn. 3.1), for H I and He I are not very density sensitive and their temperature dependences are similar, so the He$^+/H^+$ results derived using eqn. 3.8 do not depend significantly on the assumed electron density or temperature.

On the contrary, only collisionally excited lines are available for abundance determination of elements besides H and He, and these lines are much more $T_e$ sensitive. The observed forbidden line emissivities were then calculated with the FIVEL program as mentioned before, using

$$4\pi j(\lambda) = N_i A(\lambda) E(\lambda) \quad (3.8)$$

where $N_i$ is the appropriate level population, $A(\lambda)$ is the transition $A$-value, and $E(\lambda)$ is
the energy. These and the Hβ emissivities compared with the observed line intensities give the ionic abundances via eqn. 3.6. For abundance calculations, the two zone model we discussed previously was used. For [N II], [O II] and [S II] a $T_e = 8000 \, ^\circ\text{K}$ and $N_e = 400 \, \text{cm}^{-3}$ was used. $N_e = 400 \, \text{cm}^{-3}$ is the $N_e$ averaged over all the observed knots. The line emissivities, besides [S II], to an extent are quite insensitive to changes in $N_e$. For the calculation of [O III] emissivities, an electron temperature equivalent to [N II] $T_e = 8,000 \, ^\circ\text{K}$ was used for the majority of the positions as most of these lie in the inner recombination region. An [O III] $T_e$ of about 35,000 $^\circ\text{K}$ for the two positions O3spur, and NO3 was used, as these positions lie in the outer shocked region. For the [O III] emissivities, the same value of $N_e = 400 \, \text{cm}^{-3}$ was used everywhere.

The ionic abundances calculated in this manner are presented in Table 3.5. The columns give respectively, the coordinate position, and the ionic number ratio relative to $H^+$, i.e. $N(X^i) / N(H^+)$ for He II, [O II] 3727 +3729, [O III] 4959 + 5007, [N II] 6548 + 6583, and [S II] 6716 +6731. The $\text{He}^+$ result represents the average obtained from the three lines, $\lambda\lambda4471$, 5876, and 6678 weighted by 1, 3, 1 respectively.
<table>
<thead>
<tr>
<th>POSN.</th>
<th>He+</th>
<th>O+</th>
<th>O++</th>
<th>N+</th>
<th>S+</th>
</tr>
</thead>
<tbody>
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<td>8.24</td>
<td>7.65</td>
<td>8.17</td>
<td>6.10</td>
</tr>
<tr>
<td>NE1-E</td>
<td>11.18</td>
<td>8.21</td>
<td>7.66</td>
<td>8.14</td>
<td>6.17</td>
</tr>
<tr>
<td>NE2-W</td>
<td>11.17</td>
<td>8.17</td>
<td>7.44</td>
<td>8.24</td>
<td>6.15</td>
</tr>
<tr>
<td>O3spur-W</td>
<td>-</td>
<td>-</td>
<td>8.37</td>
<td>7.73</td>
<td>-</td>
</tr>
<tr>
<td>O3spur-E</td>
<td>11.20</td>
<td>7.86</td>
<td>7.81</td>
<td>7.98</td>
<td>5.82</td>
</tr>
<tr>
<td>NW1-W</td>
<td>11.25</td>
<td>7.83</td>
<td>7.90</td>
<td>7.71</td>
<td>5.54</td>
</tr>
<tr>
<td>NW1-E</td>
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<td>7.97</td>
<td>7.79</td>
<td>-</td>
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<tr>
<td>NW2-W</td>
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<td>7.63</td>
<td>7.86</td>
<td>7.75</td>
<td>5.35</td>
</tr>
<tr>
<td>W1-W</td>
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<td>7.74</td>
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</tr>
<tr>
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<td>-</td>
<td>8.64</td>
<td>-</td>
<td>-</td>
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<tr>
<td>NO3-15&quot;-W</td>
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<td>7.94</td>
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</tr>
<tr>
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<td>-</td>
<td>7.66</td>
<td>8.23</td>
<td>5.96</td>
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<td>7.44</td>
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<td>6.02</td>
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<tr>
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<td>8.15</td>
<td>7.34</td>
<td>8.28</td>
<td>6.23</td>
</tr>
<tr>
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<td>11.05</td>
<td>8.29</td>
<td>7.89</td>
<td>7.57</td>
<td>6.05</td>
</tr>
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<td>7.87</td>
<td>8.05</td>
<td>5.84</td>
</tr>
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<td>11.16</td>
<td>8.42</td>
<td>7.89</td>
<td>7.60</td>
<td>5.91</td>
</tr>
<tr>
<td>W5-W</td>
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<td>8.03</td>
<td>7.81</td>
<td>7.75</td>
<td>5.47</td>
</tr>
<tr>
<td>O3sknot-W</td>
<td>-</td>
<td>8.08</td>
<td>8.13</td>
<td>7.76</td>
<td>-</td>
</tr>
</tbody>
</table>
3.4.e. Elemental Abundances

The determination of the total elemental abundances from the knowledge of the number ratio of one or more ions of a given element relative to H⁺, requires the estimation of the ionization fractions of existing ions without observable ions. This is done by calculating approximate ionization correction factors (ICFs) based on the directly calculated O⁺ / O++ ratios (e.g. Peimbert and Torres-Peimbert 1978). For the case of He⁺, no adequate technique short of photoionization models exist for evaluation of the amount of He⁰, so we calculated the logarithmic He value based solely on the observed He⁺/H⁺ ratio for the three regions. The elemental abundance of O was found by summing the observed ionization stages:

\[ \frac{N(O)}{N(H)} = \frac{N(O^+)}{N(H^+)} + \frac{N(O^{++})}{N(H^+)} \]  

(3.9)

The total abundances using the ICFs for the other ions:

\[ \frac{N(N)}{N(H)} = [\frac{N(O)}{N(O^+)}] \times \frac{N(N^+)}{N(H^+)} \]  

(3.10)

\[ \frac{N(S)}{N(H)} = [\frac{N(O)}{N(O^+)}] \times \frac{N(S^+)}{N(H^+)} \]  

(3.11)

where the ICFs are enclosed in brackets.

The total elemental abundances for He, N, O and S are presented in Table 3.6 in the form 12 + logN(X) / N(H). At the bottom of the Table, the solar abundances, the average abundances for galactic H II regions (Shaver et al. 1983), and the mean for the He- and N- rich Type I planetary nebulae and Population I planetary nebulae (Aller 1984) are also included for comparison purposes.

The most striking feature notable from the Table is that the nebula appears to be enriched in He in all positions, by ~ 0.25 dex compared to solar and H II regions. As He⁺ was not corrected for unseen ionization stages, the given He abundances are in fact the lower limits of He. This enrichment is independent of the ionization structure, as it is seen in all the observed positions. As He is quite insensitive to the value of Tₑ used, uncertainties in Tₑ cannot account for this overabundance. The N(He) / N(H) ratio is
comparable to the high end of the range observed for the He- and N- rich planetary nebulae that Peimbert (1978) observed in the Galaxy, and indicative of a situation where the ejected material in NGC 6888 contains substantial H-burning shell and possibly even He- burning shell processed material.

The other interesting feature is the overabundance of N, particularly in the NE knots, as noted previously by Kwitter (1981) and Parker (1978). Table 3.6 shows N to be enriched by about 0.2 dex compared to solar, about 0.6 dex compared to galactic H II regions and comparable to Pop. I types, although much less than the N-rich planetary nebulae. Earlier we had demonstrated the increase in I(6584) with distance from the central star in Fig.3.8. Our abundance calculations further point to this variation being the result of ionization and not because of differences in abundances, as the N abundances seem to be quite uniform over the nebula.

Sulfur appears to be underabundant in NGC 6888. This may be due to photoionization in the recombination zone from the WR star, which may have ionized [S II] to higher ionization states. As no [S III] λ6312 was detected, the derived sulfur abundances should be considered the lower limits. The ICF used to correct for the unseen ionization stages is not completely correct in the case of S, as the [O II] and [O III] zones do not overlap with the [S II] and [S III] zones respectively, because of the difference in ionization potentials. In addition, as the [S II] λλ6716, 6731 was very weak, the uncertainty in the derivation of abundances is high. Therefore the abundances obtained using the ICFs give underestimated sulfur abundances. In the next chapter we have attempted to recalculate the S abundance using photoionization models. The oxygen abundance also appears to be depleted by about 0.3-0.4 dex in many of the positions compared to the Galactic H II regions.
<table>
<thead>
<tr>
<th>POSN.</th>
<th>HE</th>
<th>O</th>
<th>N</th>
<th>S</th>
<th>N/O</th>
<th>O/S</th>
<th>N/S</th>
</tr>
</thead>
<tbody>
<tr>
<td>NE1-W</td>
<td>11.25</td>
<td>8.34</td>
<td>8.28</td>
<td>6.20</td>
<td>-0.05</td>
<td>2.13</td>
<td>2.08</td>
</tr>
<tr>
<td>NE1-E</td>
<td>11.18</td>
<td>8.32</td>
<td>8.24</td>
<td>6.27</td>
<td>-0.08</td>
<td>2.05</td>
<td>1.95</td>
</tr>
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<td>8.31</td>
<td>6.21</td>
<td>0.05</td>
<td>2.04</td>
<td>1.99</td>
</tr>
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<td>-</td>
<td>8.44</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>O3spur-E</td>
<td>11.20</td>
<td>8.25</td>
<td>8.37</td>
<td>6.21</td>
<td>0.12</td>
<td>2.04</td>
<td>1.92</td>
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<tr>
<td>NW1-W</td>
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<td>8.17</td>
<td>8.17</td>
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<td>2.29</td>
<td>2.17</td>
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<tr>
<td>NW1-E</td>
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<td>8.21</td>
<td>8.09</td>
<td>5.72</td>
<td>-0.04</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>NW2-W</td>
<td>11.28</td>
<td>8.06</td>
<td>8.17</td>
<td>5.78</td>
<td>0.11</td>
<td>2.29</td>
<td>2.18</td>
</tr>
<tr>
<td>W1-W</td>
<td>11.33</td>
<td>8.18</td>
<td>8.12</td>
<td>6.15</td>
<td>-0.06</td>
<td>2.03</td>
<td>1.97</td>
</tr>
<tr>
<td>NO3-W</td>
<td>8.64</td>
<td>-</td>
<td>-</td>
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<tr>
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<td>8.44</td>
<td>8.12</td>
<td>6.32</td>
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<td>2.12</td>
<td>1.8</td>
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<td>8.29</td>
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<td>6.26</td>
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<td>-</td>
<td>6.02</td>
<td>-</td>
<td>1.43</td>
<td>-</td>
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<td>8.17</td>
<td>8.32</td>
<td>6.11</td>
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<td>6.00</td>
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<td>2.21</td>
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<td>6.02</td>
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<td>8.40</td>
<td>8.08</td>
<td>-</td>
<td>-0.32</td>
<td>-</td>
<td>-</td>
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</table>

| Solar     | 11.03 | 8.87 | 7.96 | 7.23 | -0.91 | 1.64 | 0.73 |
| MWG H II  | 11.00 | 8.70 | 7.57 | 7.06 | -1.13 | 1.64 | 0.51 |
| Type I PN | 11.13 | 8.71 | 8.88 | 6.98 | 0.17  | 1.73 | 1.90 |
| Pop. I PN | 11.04 | 8.68 | 8.12 | 6.96 | -0.56 | 1.72 | 1.16 |
Figure 3.1.a. 'Hα' CCD Surface Brightness 800 x 800 pixel image, showing regions of interest NE, NW, W and SW. Protruding filaments in NE are marked A21, A22. Brightness increases to the right of the colour scale as shown at the bottom.
Figure 3.1.b. Hβ CCD Surface Brightness 800 x 800 pixel Image

$8.0 \times 10^{-15} \text{ ergs cm}^{-2} \text{ sec}^{-1}$
Figure 3.1.c. [N II] Surface Brightness 800 x 800 pixel Image.

2.0 \times 10^{-14} \text{ ergs cm}^{-2} \text{ sec}^{-1}
Figure 3.1.d.  [S II] CCD Surface Brightness 800 x 800 pixel Image.
Figure 3.1.e. [O III] CCD Surface Brightness 800 x 800 pixel Image. Features of interest such as O3 Spur, A16 Arc, Bubbles in the NW and Lattice in the SE are marked.
0

1.5 $\times 10^{-14}$ ergs cm$^{-2}$ sec$^{-1}$

Figure 3.2.a. An enlargement of the North half of the H$\alpha$ image, showing the reference knots used in the 'knot' correlations.
Figure 3.2.b. Identification of the same knots as the North H\alpha reference knots, marked on the [O III], [N II] and [S II] Images as well.
Figure 3.3.a. An enlargement of the South half of the Hα image, showing the reference knots.
Figure 3.3.b. Identification of the same knots as the South Hα reference knots, marked on the [O III] and [N II] images as well.
Figure 3.4.a. Figure showing surface brightness of knots as a function of the abscissa, for North Images: Hα - o, [N II] - x, [O III] - , [S II] - x
Figure 3.4.b. Figure showing surface brightness of knots as a function of the ordinate, for South Images: Hα - o, [N II] - x, [O III] - m, [S II] - x.
Figure 3.5.a. CCD 800 x 800 pixel Image showing the Hα/ Hβ ratio.
Figure 3.5.b.  CCD 800 x 800 pixel Image showing the [O III] / Hα ratio. Features of interest such as the bright [O III] rim, [O III] Spur, bubbles in the NW, lattice in the SE and Hα knots in the NE and SW are marked.
Figure 3.5.c. CCD 800 x 800 pixel Image showing the [N II] / Hα ratio.
Figure 3.6.a. Figure showing surface brightness of North knots in the ratio images as a function of abscissa: $\text{H}\alpha / \text{H}\beta - \Delta, [\text{N II}] / \text{H}\alpha - \circ, [\text{O III}] / \text{H}\alpha - \ast, [S \text{II}] / [\text{N II}] - \lambda$.
Figure 3.6.b. Figure showing surface brightness of South knots in the ratio images as a function of ordinate: $H\alpha / H\beta - \Delta$, [N II] / $H\alpha - \sigma$, [O III] / $H\alpha - \sigma$, [S II] / [N II] - $\lambda$. 
Figure 3.7a. Reduced KPNO Spectra - positions are marked on the right of each spectra. All spectra are scaled to the lowest spectrum.
Figure 3.7b. Reduced KPNO spectra - positions are marked on the right of each.

NoAO Spectra
Separation step = 2.384196E-13
Figure 3.7.c. Reduced KPNO Spectra - positions are marked on the right of each spectrum. All spectra are scaled to the lowest spectrum. Note the decrease in [O III] line strengths relative to Hα, Hβ, and [N II] lines from the NO3 position (lowest), to positions interior to the bubble, in steps of 15″.
Figure 3.7.d. Reduced KPNO Spectra - positions are marked on the right of each spectra. All spectra are scaled to the lowest spectrum.
Figure 3.7.c. Reduced KPNO Spectra - positions are marked on the right of each spectrum. All spectra are scaled to the lowest spectrum.
Figure 3.10. This plot shows a gaussian fitted to the $\lambda4340 + \lambda4363$ combination for the NO3 position, which is not separable.
CHAPTER IV. INTERPRETATION OF RESULTS

In a complex, multi component object like NGC 6888, a huge range of excitation, electron temperatures and densities, velocities, and abundances are expected, due to the mixed interplay of photoionization from the central WR star, and shock ionization from the stellar wind pushing against the shell or ambient ISM. This play of physical processes leads to collisional excitation, photoionization and subsequent emission-line cooling of the existing ions, observable over a large range of wavelengths.

In this context, the spectrophotometry and imagery results presented in the last chapter were analysed to obtain the physical parameters of various regions of the nebula, and then correlate specific physical processes with different regions of occurrence. In order to better understand the current structure of NGC 6888 and trace it's formation and evolution history, we combined our results with previous studies of this object in other wavelengths. In this chapter we discuss and analyse:

(a) Spectrophotometry results from this study

Also, a more detailed analysis was performed by comparing the spectral results with photoionization models.

(b) CCD imagery results from this study

(c) Infrared studies with the IRAS

(d) X-Ray studies with the EXOSAT

(e) Radio Observations

(f) Velocity Information with Fabry-Perot observations

Finally, the results were interpreted and integrated into a plausible evolution scenario that was consistent with the results obtained.
IV.1. SPECTROPHOTOMETRIC ANALYSIS

IV.1.a. Spectral Comparisons with H II Regions

Diagrams of certain emission line ratios for gaseous nebulae are useful diagnostics of their ionization sources (Baldwin, Phillips and Terlevich 1981) and in limited cases, abundances. In order to further establish the nature and magnitude of the apparent abundance anomalies in NGC 6888, we adopted the procedure used by Dufour, Parker and Henize (1988) in a study of the emission-line nebula NGC 6164-5, that was motivated by the diagnostic diagrams by Baldwin et al. The variations of several emission line ratios with ionization (given by the \([\text{O II}] \lambda 3727 / [\text{O III}] \lambda 5007\) ratio) of the observed positions of NGC 6888 was compared with several galactic H II regions. The data for the galactic H II regions was adopted from the recent extensive spectrophotometry by Shaver et al. (1983). Assuming the ionization sources are similar, variations in line ratios over limited ionization ranges are likely to predominantly reflect composition variations in NGC 6888 compared to galactic H II regions.

(i) Nitrogen

In Fig. 4.1, we show a plot of \([6548/6563]\) against the ionization parameter \([3727/5007]\). The brackets i.e. \([\lambda_1 / \lambda_2]\) denote logarithmic line ratios, and this designation is maintained throughout this section. This plot shows all the observed NGC 6888 positions, which are compared against the same line ratios for 18 galactic H II regions from Shaver et al.. This figure demonstrates the N/H enrichment in NGC 6888. On comparing the regions, the ionization range appears to be similar for the nebula and the galactic H II regions, although NGC 6888 extends up to a higher ionization level. The
plot implies that N is enriched by about 1 dex. in NGC 6888 compared to galactic H II regions. This compares reasonably with the N/H results obtained from our elemental abundance calculations (Table 3.6), which shows a N/H enrichment in NGC 6888 by about 0.8 dex on average, compared to galactic H II regions.

![Fig. 4.1. BPT PLOT - H II REGIONS & NGC 6888](image)

Another nitrogen abundance indicator is the [N II] / [S II] ratio [6583/6723], as shown in Fig. 4.2 plotted vs. the ionization parameter [3727/5007] as before. The [N II] / [S II] ratio is reddening free, and also relatively insensitive to $T_e$ and $N_e$. Therefore, this ratio is indicative of the [N II]/[S II] ratio, which for the low ionization levels found here, approximates the N/S abundance. Fig. 4.2 shows that the variation in the two data sets runs parallel with ionization, with the NGC 6888 positions showing a [6583/6723] ratio
that is systematically higher than the H II regions by about 1 dex. This plot also supports a N/S enrichment in the nebula by about 1 dex as in the last figure.

**FIG. 4.2, BPT PLOT - H II REGIONS & NGC 6888**

\[ \frac{6584/6723}{[3727/5007]} \]

(ii). Sulfur

However, we note that a N/S enrichment could involve a N/H enrichment as discussed in Fig. 4.1 and/or a depletion in S/H. Fig. 4.3 compares the S/H ratio in the NGC 6888 compared to H II regions. This plot shows \[ \frac{6723/6563}{[3737/5007]} \] for both. This plot demonstrates that NGC 6888 lies along the same slope as the H II regions. This indicates that S/H in NGC 6888 is comparable to that in the H II regions. This, together with the results from Fig. 4.1 and 4.2 implies that the N/S enrichment in NGC 6888 is due to an enrichment in N/H by about 1 dex.
As the Ionization Correction Factors (hereafter I.C.F.'s) used to derive the abundance for S do not correct for the ionization stages of S properly, as discussed before, we can assume Fig. 4.3 gives results that are closer to the true existing values in the nebula than those obtained in Table 3.6. We can thus assume that S/H is similar to the H II regions abundance. Assuming a value of S/H that is similar to that of the H II regions, also brings down the N/S ratio in Table 3.6 by about a dex, making it enriched by about a dex compared to galactic H II regions. The result after this correction agrees with the N/S enrichment of 1 dex shown in Fig. 4.3.
IV.2. Abundance Anomalies

In Chapter III, the abundance diagnostics (Table 3.6) indicated that NGC 6888 is enriched in N and He compared to solar and galactic H II region abundances. These anomalies are discussed here in more detail:

Nitrogen:

The nitrogen abundance relative to hydrogen, i.e. N/H in the NGC 6888 knots, demonstrates an enrichment by about 0.5 dex compared to galactic H II regions. The N/H ratio is similar to that of Pop. I planetary nebulae, and enriched by about 0.5-0.6 dex. compared to Galactic H II regions. Although N/H is less than that observed in Type I (Peimbert 1978) by 0.4-0.5 dex, the N/O ratio is similar due to the lower O/H.

Type I PN show enhanced nitrogen and helium abundances, which is a result of progenitors that are more massive than those of most planetaries, or because of greater mixing within the envelope of the star prior to nebular ejection. These objects tend to be filamentary and morphologically similar to NGC 6888.

Figs. 3.8 and 3.9 argues for the variation in the [N II] lines over the different regions being predominantly due to variations in ionization over the nebula as a function of distance from the star. This is because of a dilution in ionizing photons as a function of distance.

Kwitter (1981) and Parker (1978) had suspected that the variation in [N II] \( \lambda 6583/ \) H\( \alpha \) over the nebula was due to ionization variations, but also considered the possibility that a non-uniformity in abundances over the different regions could be the cause. The uniformity in the total elemental abundance for N/H demonstrated in Table 3.6, independent of location in the nebula indicates that ionization variations and not abundance variations is the prime cause for observed N/H variations.
Helium:

The He abundance is also found to be significantly enhanced in NGC 6888, compared to solar, MWG H II regions and even some Type I PN. As mentioned before, the value of the He abundance presented in Table 3.6 is the lower limit, as corrections for the presence of neutral helium have not yet been performed. It is interesting that in spite of the high He abundance He II λ4686 is not observed. The absence of He II λ4686 may imply that the ionizing star may not be hot enough to radiate an appreciable number of photons with hv > 54.4 ev.

It is well established that the Type I PN are enriched in both N and He relative to H (Kaler 1979). Both enrichments are attributed to the mixing of CNO-processed material in the ejected envelope prior to ejection. This suggested that the material observed in the NGC 6888 shell is also partly due to material shed by the central star in the process of becoming a WR star. We note that the N/H ratio in the knots of NGC 6888 is higher than the galactic H II regions by a factor of 3 or higher. Enrichment at such a large scale suggests that material came from the star and indicates the presence of large scale processing inside the WR star prior to mass loss. We discuss this enrichment quantitatively in a later section.

Torres-Peimbert and Peimbert (1977), and Kaler (1978) noted the existence of significant enhancement of He in some planetary nebulae, and established a definite correlation between the He and N enrichment in planetary nebulae. Kaler, Iben and Becker (1978) demonstrated that this correlation agrees with predictions made by theories of stellar evolution. Figure 4.4 shows the N and He abundance correlations of several planetary nebulae (Φ), taken from Torres-Peimbert and Peimbert (1977). N(He)/ N(H) and log N correlations of the observed positions of this study (⊙) are superposed on the
same plot. This plot shows that there is no distinct correlation between the N and He abundances in the case of NGC 6888, which suggests that the processing in WR stars may follow a different route. A noteworthy fact demonstrated by this figure is that the N(He)/N(H) ratio is significantly higher than that found for the PN. This is not surprising as WR stars are believed to be helium stars, i.e. in the He burning stage (Underhill, 1977). WN stars in particular, are thought to be at the stage where most of the carbon and oxygen has been processed through the CNO cycle into N (Paczynski 1973), which could account for the nitrogen enrichment.

**FIGURE 4.4 N to He Correlation**

![Graph showing N(He)/N(H) ratio vs. N]

**Oxygen, Sulphur:**

The mean O/H abundance in NGC 6888 seems to be (Table 3.6) depleted by
about 0.3-0.4 dex compared to solar, galactic H II regions and Type I PN. This points to the high N/O in NGC 6888; i.e. comparable to Type I PN, being due to the O depletion. We discuss the O/H depletion in a later section when we obtain elemental abundances through photoionization models.

**Sulfur:**

O/S is larger than the solar and H II regions ratio by 0.4-0.5 dex. N/S is also found to be higher than the solar and H II regions by about 1.3 and 1.5 dex respectively. As stated before, the abundances of Ne and S are not well determined. The S abundances should be taken as the lower limits, as no [S III] λ6312 was detected, and the ionization correction used does not correctly compensate. Also, there are some uncertainties involved in the determination of the abundances because of the weakness of the [S II] λ6716, 6731 line strengths.

The elemental abundances vary over the different regions of the nebula to a small but noticeable extent, by about 0.3 dex. between the lower and higher abundance values. This is true especially in the case of sulfur, which may be a result of incorrect ionization corrections. We will discuss the ionization fractions, abundances and their dependence on various nebular parameters in the following section, where we use them to develop photoionization models.

**IV.2. PHOTOIONIZATION MODELS**

NGC 6888 has been found to have a rich spectrum of emission lines covering a wide range of elements and existing ionization stages. The presence of large variations in T_e, N_e and ionization over the nebula complicates the analysis for abundance determinations, etc. even further. A detailed model of the ionization structure of the
nebula is therefore needed to derive more accurate values of abundances.

The photoionization model code developed by Shields (1978), was run for two of the NGC 6888 positions. This code calculates model H II regions in a spherical, optically thick nebula ionized by a hot, stellar continuum. Standard techniques are used to solve for the equations of photoionization and thermal equilibrium, line emission, and radiative transfer, following the theory given by Osterbrock (1974). Photoionization cross sections and atomic parameters used in the model calculations are referenced in Shields. Photoionization and heating rate integrations were performed using a grid of 70 frequencies between 0.58 Ryd. and 4.0 Ryd. All important ionization potentials were included in this grid, and discontinuities were replaced by using 'infinitesimal' frequency intervals spanning them. Radial integrations were started at an initial $R_{\text{min}}$ and continued up to the radius at which the ionizing photons were completely absorbed. The diffuse radiation in the Lyman continuum of H I and He II was treated in the 'on the spot' approximation.

The models were characterized by specific values of ionizing continuum luminosity $L_\nu$ (ergs s$^{-1}$ Hz$^{-1}$), a filling factor $\phi$, a gas density $N$ (cm$^{-3}$), and a set of elemental abundances. A scaling factor $L_0 = L_\nu (v_H)$ was used in the input to adjust $L_\nu$ to the appropriate $Q(H^0)$, which is the number of ionizing photons per unit of time as determined from the H$\beta$ luminosity, where

$$Q(H^0) = \int \frac{L_\nu}{h\nu} \, d\nu$$  \hspace{1cm} (4.25)

$Q(H^0)$ was determined to be $8 \times 10^{47}$ photons s$^{-1}$ from the observed integrated H$\beta$ luminosity of $4 \times 10^{35}$ ergs cm$^{-2}$ s$^{-1}$ for NGC 6888. The ionizing stellar spectrum was
adopted from the stellar atmosphere models by Hummer and Mihalas (1970b). A stellar
temperature $T_{\text{eff}} = 55,000$ °K for log $g=4.0$ was used.

Initially, average observed elemental abundances as presented in Table 3.6
for He, N, O and S were input into the model. An abundance for C was obtained
assuming a solar C/N ratio. On the other hand, abundances for Ne, Mg, Si, and Ar were
used assuming solar Ne/O, Mg/O, Si/O and Ar/O ratios, where the solar values were

The conditions of success of the model was defined to be the general
agreement of the [N II] and [O III] $T_e$'s and the degree of ionization between the model
and the observed results, within the observational constraints. The gas density $N$ and
filling factor $\varepsilon$ terms in the model were adjusted to give the correct ionization level as
defined by the observed $O^+ / O^{++}$, i.e. $\lambda\lambda3726+3729 / \lambda5007$ ratio. The ionization
parameter $U$ as defined below constrains the degree of ionization. Increasing values of $U$
correspond to higher ionization, and therefore lead to larger values of $O^{++} / O^+$.

$$U = \frac{Q(H^0)}{4\pi R_s^2 N \varepsilon} \quad (4.1)$$

where $Q(H^0)$ is the number of ionizing photons from the ionizing source, $R_s$ is the
Stromgren radius and $N$ is the gas density. $U$ is changed in the model by adjusting the
values of $N$ and $\varepsilon$. Other constraints placed on the model outputs were correct matches to
the [N II] $\lambda 6583$, He I $\lambda 5876$ and [S II] $\lambda\lambda6716, 6731$ observed line intensities. For this
reason the initial N abundance was adjusted to agree with the 6583 line intensity after the
[O II]/[O III] ratio was fit. Finally the O abundance in the input was also changed to give
not only the correct ionization, i.e. [O II]/[O III] ratio, but also individual emission lines
like [O II] $\lambda 3736,3729$ and [O III] $\lambda 5007$.

The model output determines line intensities, ionic fractions $<X(A^{+i})>$ and weighted ionic temperatures $<T(A^{+i})>$ for the ionic states $A^{+i}$ for a specific element, where:

$$<X(A^{+i})> = \frac{\int N(A^{+i}) N_e dV}{\int N(A) N_e dV}$$  \hspace{1cm} (4.2)$$

and

$$<T(A^{+i})> = \frac{\int T N(A^{+i}) N_e dV}{\int N(A^{+i}) N_e dV}$$  \hspace{1cm} (4.3)$$

where $N_e$ is the electron density. The model temperatures thus determined were used in conjunction with the model ionic fractions to calculate final ionic and elemental abundances.

**MODELS USED:**

The photoionization model was run for two of our knot positions (Ref. Table 2.6), NE-2W and NW1-W, as these two positions differ significantly in physical parameters, abundances and ionization as defined by [O II]/[O III] and particularly [O III] / Hα and [N II] / Hα, and location in the nebula. Table 4.1 lists the input parameters like abundances, Rmin- the starting radius and the input chemical abundances, for the NE2 and the NW1 position that were used for the models.
Table 4.1. INPUT PARAMETERS for MODELS

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<td>[O III] 5007</td>
<td>1.05</td>
<td>2.53</td>
<td>1.06</td>
<td>3.1</td>
</tr>
<tr>
<td>[O III] 4363</td>
<td>0.05</td>
<td>0.02</td>
<td>0.01</td>
<td>0.04</td>
</tr>
<tr>
<td>[S II] 6731</td>
<td>0.14</td>
<td>0.15</td>
<td>0.17</td>
<td>0.03</td>
</tr>
<tr>
<td>[S II] 6716</td>
<td>0.17</td>
<td>0.20</td>
<td>0.22</td>
<td>0.03</td>
</tr>
<tr>
<td>[O II]/[O III]</td>
<td>1.20</td>
<td>1.20</td>
<td>1.20</td>
<td>0.18</td>
</tr>
<tr>
<td>U (x 10^{-4})</td>
<td>2.44</td>
<td>2.28</td>
<td></td>
<td>20.0</td>
</tr>
<tr>
<td>Rs (10^{20})cm</td>
<td>0.9</td>
<td>0.98</td>
<td>0.73</td>
<td>0.45</td>
</tr>
</tbody>
</table>
### Table 4.3. Photoionization Model Results

<table>
<thead>
<tr>
<th></th>
<th>NE2-2</th>
<th>NW1-2</th>
<th>NE2-2</th>
<th>NW1-2</th>
</tr>
</thead>
<tbody>
<tr>
<td>(&lt;X(H+)&gt;)</td>
<td>0.912</td>
<td>0.98</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(&lt;X(He+)&gt;)</td>
<td>0.94</td>
<td>0.99</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(&lt;X(\text{N II})&gt;)</td>
<td>0.57</td>
<td>0.12</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(&lt;X(\text{N III})&gt;)</td>
<td>0.39</td>
<td>0.72</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(&lt;X(\text{O I})&gt;)</td>
<td>0.09</td>
<td>0.02</td>
<td>0.951</td>
<td>1.02</td>
</tr>
<tr>
<td>(&lt;X(\text{O II})&gt;)</td>
<td>0.52</td>
<td>0.16</td>
<td>1.07</td>
<td>1.17</td>
</tr>
<tr>
<td>(&lt;X(\text{O III})&gt;)</td>
<td>0.39</td>
<td>0.82</td>
<td>1.13</td>
<td>1.20</td>
</tr>
<tr>
<td>(&lt;X(\text{S II})&gt;)</td>
<td>0.20</td>
<td>0.04</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(&lt;X(\text{S III})&gt;)</td>
<td>0.76</td>
<td>0.64</td>
<td>1.10</td>
<td>1.20</td>
</tr>
</tbody>
</table>

### Table 4.4. Elemental Abundances from Models

\(12 + \log N(X)/N(H)\)

<table>
<thead>
<tr>
<th></th>
<th>N</th>
<th>O</th>
<th>S</th>
</tr>
</thead>
<tbody>
<tr>
<td>NE-2</td>
<td>8.17</td>
<td>7.83</td>
<td>6.64</td>
</tr>
<tr>
<td>NW-1</td>
<td>8.02</td>
<td>7.88</td>
<td>6.57</td>
</tr>
<tr>
<td>Solar</td>
<td>7.96</td>
<td>8.87</td>
<td>7.23</td>
</tr>
<tr>
<td>MWG H II</td>
<td>7.57</td>
<td>8.70</td>
<td>7.06</td>
</tr>
<tr>
<td>Type I PN</td>
<td>8.88</td>
<td>8.71</td>
<td>6.98</td>
</tr>
</tbody>
</table>
ANALYSIS OF MODEL RESULTS:

NE-1

The individual line intensities obtained by fitting the model for NE-2 and NW-1, as well as the observed emission lines for comparison purposes are presented in Table 4.2. Model NE-1 was fit to have the required O⁺/O++ ratio as defined by 3727/5007 = 1.2, as well as correct λ6583, λ5876 and λ6716+6731 values. From Table 4.2 we note that both the [O III] and [N II] Tₑ's determined by this model are higher than the observed Tₑ although within the limits of observational errors. Following our discussion of section III.3.c, most of the [N II] emission comes from the knots; and therefore the [N II] Tₑ is more representative of the true situation in the knot.

It is noteworthy that using the observed O abundance = 1.7 x 10⁻⁴ in the input gives 3727,3729 and 5007 line intensities in the output of the model that are 2-3 times larger than the observed line intensities. Raising the O abundance in the input would result in a decrease of Tₑ, and bring it closer to the observed value as O is an important coolant. Using an O abundance equalling the solar O abundance (∼ 6 x 10⁻⁴), in the model gave emission line intensities that were a factor of 4-5 times higher than that observed. This indicates that O is intrinsically underabundant in this position.

We note that the above result is somewhat doubtful, as we decreased the O abundance in the input but not the other emission lines. This could shift the cooling to the lines of other heavy elements such as N.

Model NE-2 is a 'best fit' model with correctly matched line intensities as well as ionization ratio, and Tₑ within the observational errors. This model used an O abundance that is deficient by ∼ 9 compared to the solar abundance to fit the observed [OIII] emission lines. The N abundance also had to be lowered from the initial observed
value to fit the intensity of the observed [N II] $\lambda 6584$ line. The N abundance used in the final model, Model NE-2 still appears to be enriched compared to solar, as discussed in previous sections, although by a less significant amount.

The physical parameters used in fitting NE-1 are similar to those found to be prevalent observationally. The gas density used was 200 cm$^{-3}$, which compares with the $N_e \approx 300$ cm$^{-3}$ determined by the [S II] 6716/6731 for the NE knot. The value of $R_s \approx 7 \times 10^{18}$ cm, as calculated by the model is also similar to the major axis length of $9 \times 10^{18}$ cm.

NW-1 POSITION:

This position has a distinctly different [O II]/[O III] ratio $\approx 0.18$, in comparison with the ionization ratio of 1.2 observed in the NE. An attempt was made to fit the lower ionization level in the NW1 position simply by changing the ionization parameter U in the NE2 model, keeping abundances constant as determined by the NE2 model. This would prove that the observed regional variations in [N II], [O II] and [O III] line intensities are due to a direct result of ionization variations. To achieve such a low ionization level, physical parameters like the filling factor $\varepsilon$ and the gas density N had to be changed drastically, and as a result, the ionization parameter was significantly different in NW2 ($\approx 1.9 \times 10^{-3}$) as compared to that in the NE1 $\approx 2.3 \times 10^{-4}$. Model NW1-1 presents the line intensities, and ionization and temperature fractions obtained by keeping the abundances fixed, and only increasing the ionization parameter U. Similar to Model NE-1, the [O III] and [N II] $T_e$'s are lower than the observed $T_e$'s in the NW1-1 results, but within observational errors. The individual line intensities of 3727 and 5007 are also higher than the observed lines, by a factor of about 2. This demonstrates that the variation in the intensity of the observed lines from NE 1 to NW2, using the [O II] 3727, [O III] 5007 and [N II] 6584 intensities as examples cannot be a result of ionization.
alone.

Model NW-2 fits the individual line ratios, as well as the ionization ratio by lowering the O and the N abundances in the input. The O abundance required to fit the observed emission appears to be underabundant compared to solar also in this case, by a factor of 10.

We note that NE2 is representative of all the knots in the NE, as the emission line intensities are quite uniform over NE, and NW1 is similarly representative of the knots in the NW. The models thus indicate that ionization variations are the dominant reason for the variations in emission line intensities from NE to NW; and abundance variations play a smaller but significant role. The ionic and temperature fractions calculated for the NGC 6888 models are presented in Table 4.3, along with calculated ionic abundances. Table 4.4 gives the elemental abundances derived for these models. The ionic and elemental abundances were calculated using the method described in Shields et al. (1981).

We can now confirm the idea we had proposed before suggesting that the ionization structure is a function of distance from the star, using distances to knots that are now corrected for orientation and projection (from the last section). For this purpose, we selected our NE2-W and NW1-W positions, as these are the same positions we used in the photoionization model discussed in the next section.

The NE position lies at the end of the major axis of the ellipse. This region is tilted towards the observer by 20-40° from the plane of the sky, according to the model discussed. Assuming a 30° tilt, therefore the true distance to this position is given by:

\[
\text{True dist}_{\text{NE2}} = \frac{\text{Projected( observed) dist}_{\text{NE2}}}{\cos 30°}
\]

\[
\text{True dist}_{\text{NE2}} = 528'' / \cos 30° = 610'' = 4.3 \text{ pc.}
\]

On the other hand, NW1 lies close to the minor axis, and therefore lies along
the plane of the sky, and does not have to be corrected for projection.

True dist. $NW_1 = 216'' = 1.52$ pc.

The ratio of the squares of the distances gives:

$$\frac{R_{NE2}^2}{R_{NW1}^2} = \frac{(610'')^2}{(216'')^2} = 7.9 \quad (4.4)$$

Whereas, the ratio of ionization of the two positions as given by the best-fit model results is given by:

$$\frac{\text{Ionization - NE2-2}}{\text{Ionization - NW1-2}} = \frac{(3727 / 5007) - NE2-2}{(3727 / 5007) - NW1-2} = \frac{1.2}{0.18} = 6.7 \quad (4.5)$$

This confirms that ionization is a function of distance from the star within observational error constraints, as had been speculated before.

Another important result from the runs of this photoionization model is that O/H appears to be significantly depleted in NGC 6888, in both the NW1 and NE2 position, by about 1 dex. compared to solar and about 0.9 dex compared to MWG H II regions. On the other hand, the model shows NGC 6888 to have N/H enriched by about 0.1-0.2 dex compared to solar and by about 0.4-0.6 compared to galactic H II regions, not as high as the NE knots measured before. Although the significant oxygen depletion is surprising, other known shell nebulae, notably the condensations around η Car (Davison et al. 1986) and the AG Car shell (Mitra and Dufour 1990) also show evidence for O/H depletion by about two and one orders of magnitude respectively, compared to solar. NGC 6888, similar to these examples may be going through some kind of 'oxygen depleting' process before the shell ejection phase. Torres-Peimbert (1984) has previously
noted the probable existence of a nucleosynthetic process that converts O into N in the shells of Type I PN, based on the result that O and N seem to be anticorrelated in these PN (believed to come from more massive progenitor stars than most PN).

In order to examine if photoionization is really the primary cause of ionization in NGC 6888, compared to shock or non-thermal sources, we adopted the procedure described by Baldwin et al. (1981). Baldwin et al. showed empirically that combinations of emission-line ratios could be used to separate objects into four categories depending on their primary excitation mechanism: normal H II regions, planetary nebula, photoionization by a power-law continuum, and shock ionization. Fig. 4.5 shows a plot of $\lambda3727/\lambda5007$ vs. $\lambda6583/\lambda6563$ adopted from Baldwin et al. that has the same ratios for NGC 6888 superposed on it. The parentheses denote logarithmic line ratios, as discussed in the last chapter. The Baldwin data shows four distinct zones corresponding to the four excitation mechanisms, where normal H II regions, planetary nebulae, objects photoionized by power law, shock-ionized objects, and NGC 6888 positions are plotted. The NGC 6888 ratios are seen to lie mainly on the locus of objects that are photoionized by power law. However, we note that the knots of NGC 6888 were found to be enriched in N by about 0.6 dex. compared to galactic H II regions, from Table 4.4. We compensated for this by moving the points down the ordinate by 0.6 dex in the same figure. Also an [O III] $T_e$ of about 13,000 °K was obtained in the model for this nebula, which in comparison to a value of $T_e \sim 8000$ °K in H II regions, puts NGC 6888 in a higher ionization level ($3727/5007$). Therefore, we compensated for the ionization in NGC 6888 by estimating the [3727/5007] ratio for a $T_e$ of 8000 °K. This correction moved the points to the right side of the abscissa by about 0.5 dex; i.e. the ionization level was lowered. The direction of both the corrections are shown by some examples of arrows that connect the old and the corrected positions in the plot. The corrected points
indicate that NGC 6888 lies along the locus of the [H II] regions. As H II regions have
potoionization by normal O and B stars as their primary excitation mechanism, this plot
implies that NGC 6888 is also being photoionized by a hot star, which is the WN star.

Fig. 4.6 shows a similar plot using the reddening independent line ratios
[5007/4861] vs. [6584 / 6563] for the same objects as the last plot and NGC 6888. This
plot places the NGC 6888 points along the locus defined by the shock-ionized objects.
We went through a correction process for the NGC 6888 points as in the previous case
by decreasing [6584/6583] by a factor of 0.6 dex along the abscissa, to compensate for
the N enrichment in the nebula compared to H II regions. Table 4.4 also showed [O III]
to be depleted by about 0.9 dex compared to H II regions. To correct for this, the points
were increased along the ordinate by 0.9 dex. Again, the connecting arrows show the
direction of correction. This correction again places NGC 6888 close to the locus of
galactic H II regions, and the two plots are seen to lead to the same conclusion. These
plots thus support our assumption that photoionization is the dominant mode of excitation
in NGC 6888, and thus the use of the photoionization model in this case is appropriate.

In the BPT plots discussed (Fig. 4.5 and 4.6) the NGC 6888 positions
demonstrated a spread along the locus where they were situated. Binette (1985) plotted
photoionization models for liners as a function of varying ionization parameter U, for
different power laws. He demonstrated that a spread in the abscissa i.e. along the [O II]/
[O III] ratio value, corresponds to different U's. This is shown in Fig. 4.7, which shows
[5007/4861] vs. [O II] / [O III] for his models, as well as NGC 6888 positions. This
figure explains the spread observed along the abscissa in Figs. 4.5 and 4.6 as being due
to changing U as well. Fig. 4.8 shows the same abscissa [O II]/ [O III] now plotted
versus projected distance from the WR star. Fig 4.8 demonstrates that [O II]/[O III] and
therefore the varying ionization parameter values are directly dependent on projected distance from the star.

IV.3. **CCD IMAGERY RESULTS**

IV.3.a. i). **Optical Luminosity**

The intensity values in the final corrected and calibrated surface brightness CCD images were added over all the pixels to give an integrated surface brightness value for each image. These values were then corrected for reddening, assuming a reddening \( C(\text{H} \beta) = 0.92 \). This value of \( C(\text{H} \beta) \) was the average value of the reddening constant from all the positions observed in our spectrophotometry.

Interstellar extinction makes the observed ratio of intensities of two emission lines \( F_{\lambda_1} / F_{\lambda_2} \) differ from the ratio as emitted in the nebula \( I_{\lambda_1} / I_{\lambda_2} \), in the following way:

\[
\frac{I_{\lambda_1}}{I_{\lambda_2}} = \frac{F_{\lambda_1}}{F_{\lambda_2}} \cdot 10^{C \{ f(\lambda_1) - f(\lambda_2) \}}
\]

(4.6)

From 4.6,

\[
\log \frac{I(\lambda)}{F(\lambda)} = \log \frac{I(\text{H} \beta)}{F(\text{H} \beta)} + C(\text{H} \beta) f(\lambda)
\]

(4.7)

From 4.7,

\[
\log I(\lambda) = \log F(\lambda) + C [1 + f(\lambda)]
\]

(4.8)

From the values of \( f(\lambda) \), from Seaton (1979), we have for the specific emission lines:

\[
\log I(5007) = \log F(5007) + 0.966 \, C
\]

\[
\log I(6563) = \log F(6563) + 0.677 \, C
\]
\[ \log I(6583) = \log F(6583) + 0.674 \, C \]
\[ \log I(6723) = \log F(6723) + 0.656 \, C \]

The integrated surface brightness \( F(\lambda) \), and reddening corrected brightness \( I(\lambda) \) for each emission line is presented in Table 4.5.

<table>
<thead>
<tr>
<th>Image</th>
<th>Integrated Fluxes (ergs cm(^{-2}) sec(^{-1}))</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>( F(\lambda) )</td>
</tr>
<tr>
<td>H(\alpha)</td>
<td>( 7.55 \times 10^{-10} )</td>
</tr>
<tr>
<td>H(\beta)</td>
<td>( 1.88 \times 10^{-10} )</td>
</tr>
<tr>
<td>[NII]</td>
<td>( 5.77 \times 10^{-10} )</td>
</tr>
<tr>
<td>[OIII]</td>
<td>( 4.31 \times 10^{-10} )</td>
</tr>
</tbody>
</table>

Assuming a distance of 1.45 Kpc (Wendker et al 1975), the H\(\beta\) flux corresponds to an H\(\beta\) luminosity of

\[ L(H\beta) = 4.0 \times 10^{35} \text{ ergs s}^{-1} , \quad (4.9) \]

Similarly, the H\(\alpha\) flux leads to an H\(\alpha\) luminosity of

\[ L(H\alpha) = 7.9 \times 10^{35} \text{ ergs s}^{-1} \]

This H\(\alpha\) luminosity is comparable to Marsden and Meaburn's (1988) H\(\alpha\) luminosity of \( 7 \pm 3 \times 10^{35} \text{ ergs s}^{-1} \); which was estimated by integrating the average absolute H\(\alpha\) brightness found along the slit length across the major axis over the whole solid angle of the nebula.
IV.3.b. **Lyman Continuum Flux**

Meaburn (1983) gives the following equation to calculate the number of Lyman continuum photons needed to create the observed integrated Hα flux:

$$ Q_{\text{Lyc.}} = 6.8 \times 10^{49} \ I(\text{Hα}) \ D^2 \ \text{photons s}^{-1} \quad (4.10) $$

where $D$ is the distance to the nebula in parsecs.

Therefore, for the observed Hα flux:

$$ I(\text{Hα})_{\text{integrated}} = 3.18 \times 10^{-9} \ \text{ergs cm}^{-2} \ \text{sec}^{-1} $$

This gives a value of $S_{\text{Lyc.}} = 4.5 \times 10^{47} \ \text{photons s}^{-1}$.

For a WN 6 star, Barlow, Smith and Willis (1981) give the available photon flux

$$ Q_{\text{Lyc.}} = 1.0 \times 10^{49} \ \text{photons s}^{-1}. $$

This indicates that HD 192163 has more than the number of photons necessary to keep the observed shell region ionized. Therefore, the observed part of the nebula should be fully ionized.

On the other hand, the ionization parameter $U$, which determines the level of ionization is given by

$$ U = \frac{Q(\text{H}^0)}{4\pi R_s^2 N_c} \quad (4.10) $$

where $R_s$ is the stromgren radius, and $N$ is the gas density. This parameter determines the fractional abundances of the different ionization stages of the ions. The gas density $N$ is much higher in the knots ($\sim 400 \ \text{cm}^{-3}$ on average), compared to the density in the diffuse interspersed material, which together constitute the whole emitting region. This is apparent from the surface brightness Hα image, which shows the knots to be much brighter than the diffuse material. As discussed previously $I(\text{Hα}) \sim N_e^2$, which implies
that the knots have a higher $N_e$. As a result, $U$ is possibly lower in the knots and there is a possibility that the knots are not fully ionized, but have neutral cores. Actually, neutral lines such as [O I] $\lambda 6300$ was observed only in a couple of the positions, ex. NE2-W.

IV.3.c. Filling Factor

The filling factor, $f$, is approximately the fraction of the volume that contains relatively high-density forbidden-line emitting material. The filling factor can be calculated from the ratio of the electron rms density derived from the H$\beta$ surface brightness and the density from forbidden lines, $N_e$(FL), such as the [S II] line ratio:

$$f = \frac{[N_e(rms)]}{N_e(FL)}$$

Adopting the method in Torres-Peimbert and Peimbert (1977), the electron rms density $N_e(rms)$ for an ideal homogeneous spherical nebula of radius $r$ can be calculated using:

$$N_e^2(\text{RMS}) = \frac{3d^2I(\text{H}\beta)N_p(\text{RMS})}{r^3\alpha(\text{H}\beta)E(\text{H}\beta)}$$  \hspace{1cm} (4,11)

where $d$ is the distance to the nebula, $I(\text{H}\beta)$ is the corrected H$\beta$ flux, $N_p(\text{rms})$ is the proton rms density ($= 1 + \text{He}^+/\text{H}^+ + \text{He}^{++}/\text{H}^+$), $\alpha(\text{H}\beta)$ is the effective recombination coefficient for H$\beta$, and $E(\text{H}\beta)$ is the energy of an H$\beta$ photon. For a distance $d = 1.45$ pc, radius for the nebula 2.95 pc, and using $\alpha(\text{H}\beta) = 3.04 \times 10^{-14}$ cm$^{-3}$ sec$^{-1}$ (Osterbrock 1974), we get for the entire nebula:

$$N_e(\text{rms}) \sim 35$$

Where $N_p = 1 + 0.17$, as $\text{He}^+/\text{H}^+ = 0.17$ on average from our spectrophotometric results, and He$^{++}$ was not observed.

An average electron density $N_e = 400$ cm$^{-3}$ derived from the [S II] line ratio...
for the knots. This value gives us a filling factor

\[ f = \left( \frac{N \text{ rms}}{N_e \text{ F.L.}} \right)^2 = \left( \frac{35.2}{400} \right)^2 = 0.008. \]

This filling factor is low compared to the average value of \( f = 0.05 \) obtained by Torres-Peimbert and Peimbert (1977) in the study of 48 planetary nebulae. This suggests that NGC 6888 is a large, extended clumpy nebula with a very low filling factor. Assuming the whole volume of the observed region to be spherical, the volume is given by \( V_{\text{neb}} = \frac{4}{3} \pi R^3 = 107 \text{ pc}^3 \) (Using \( R = 2.95 \text{ pc} \)). A filling factor \( f = 0.008 \) therefore gives an emitting volume = 0.8 pc³, for the nebula.

IV.3.d. **MASS OF THE NEBULA**

The mass of associated ionized hydrogen NGC 6888 can be calculated using (Marsden and Meaburn 1988):

\[ M_{\text{HII}} = 70.2 \left( I_{\text{H\alpha}} D^2 \right) \left( V_{\text{HII}} \right)^{0.5} M_\odot \]

(4.12)

Where \( V_{\text{HII}} \) is the volume of emitting gas, which is calculated to be 0.8 pc³ from the value of the calculated filling factor, \( D \) is the distance to the nebula in pcs. Using our estimated value of integrated \( I_{\text{H\alpha}} = 3.2 \times 10^{-9} \text{ ergs cm}^{-2} \text{ sec}^{-1} \), \( d = 1.45 \text{ kpc} \) gives \( M_{\text{HII}} = 4.9 M_\odot \).

This is comparable to the mass obtained by Treffers and Chu (1982) \( \sim 5 M_\odot \), and Kwitter (1981) \( \sim 4.5 M_\odot \). We note that this is the mass of only the ionized material in the shell, and does not take into consideration the existence of neutral material. This is because this mass is estimated from the observed Hα luminosity, and any existing neutral material would not be observable in Hα.

On the other hand, Marsden and Meaburn (1988) estimated a gas mass of 43 \( M_\odot \) from IRAS data. This was based on the assumption that 90% of the shell mass is actually made of neutral material. We will discuss the existence of neutral material relative to the position of the ionized shell in the next section.
At this point in our discussion of the physical properties of the nebula, we will digress to a discussion on recent IRAS information that allows us to re-evaluate the mass of the nebula.

IV.4. MASS DETERMINATION USING IRAS:

The IRAS imaging presents a new opportunity to study the interactions of hot luminous stars with the material that surrounds them. Even though the typical optical depth in dust within 10 pc of a hot star is $10^{-2}$, this fraction of the star's bolometric luminosity converted to the infrared has a significant flux in the IRAS detectors. Dust heated by starlight thus provides an excellent gas tracer for warm regions with normal dust-to-gas ratio.

a. The existence of neutral material?

Marsden and Meaburn (1988) proposed that IRAS survey maps revealed a shell of neutral material in NGC 6888 that contained 40 $M_\odot$. This hypothesis hinged on the assumption that the major part of the far-infrared continuum was due to warm dust and not line emission.

Emission was seen over the entire nebula in the 4 IRAS bands - 12 $\mu$m, 25 $\mu$m, 60$\mu$m and 100 $\mu$m. The cool (25 K) dust was best seen in the 100 $\mu$m band, whereas the warmer (47 K) emission was in the northern part of the nebula and was observable in the 25 and 60 $\mu$m bands. The larger reddening values found in the north (as mentioned in Chapter III, especially for the NE region) in visible observations supports the existence of relatively more dust in the north-east part of the nebula. Marsden and Meaburn considered the line emission contribution to be the worst case of 30%, following Pottasch's (1985) proposition that between 5 to 30% of planetary nebulae far-IR emission in the IRAS 60 and 100 $\mu$m bands is due to line emission.
Assuming a 30% line contribution and an average dust temperature of 33K led to a
dust mass estimate of 0.3 ± 0.1 M⊙. Assuming a gas to dust mass ratio of 100 gave 30
M⊙ of swept up neutral material. In comparison, the ionized mass was determined to
be only about 5 M⊙.

As a result, Marsden and Meaburn concluded that approximately 90% of the
shell mass was made up of neutral material. This conclusion was based on the
assumption that far infrared emission lines of nitrogen and oxygen contribute little to the
observed far IR emission, which seems likely as only a small fraction of the gas is found
to be ionized.

b. Emission-line contribution to IRAS?

Van Buren & McCray (1988) on the other hand hypothesised that the infrared
emission from NGC 6888 was dominated by emission lines (from [N II] and [O III]) as
observed in the IRAS Low Resolution Spectrometer spectrum of NGC 6888, an
example of which shown in Fig. 4.9. The two broad features in the figure are due to the
Ar III 9.0 μm and Ne III 15.5 μm lines. Therefore they could not fit the spectrum with a
reasonable emissivity law and a small range of dust temperatures. This led them to
believe that line emission dominated the infrared emission.

Another factor supporting this hypothesis was that NGC 6888 is unique
compared to planetary nebulae as it has a high pressure, i.e. nT ~ 10^7 cm⁻³ K. Higher
pressure objects have a higher contribution of emission lines in the IR, as dust emissivity
~ n, whereas line emissivity ~ n² making it likely that high pressure objects would be
more dominated by emission lines in the infrared.

c. Extrapolation from the optical to solve this problem:
From our calibrated imagery pictures, we note the similar morphological appearance of the IRAS 60μm image with our [O III] and to some extent the [N II] images, as shown in Figs. 4.10 a,b,c. Our calibrated [O III] and [N II] full field surface brightness images were used in order to extrapolate from the optical line emission to the IR emission, to study the contamination of the observed IRAS flux by emission line contribution.

A. DIVISION INTO TWO ZONES:

As the [O III] emission region is spread out over two distinctly different morphological (and physical) regions, the line emissivities $J$ which are functions of $T_e$ and $N_e$, will be very different in the two zones. The [O III] emissivities are very sensitive to changing $T_e$, as shown in Fig.4.11. Therefore, using a single average value of $T_e$ for the whole nebula would lead to erroneous values of emissivities for $\lambda$5007 and $\lambda$88 μm, and as a result, the wrong estimate for the extrapolated contribution of [O III] $\lambda$88 μm. Therefore, it seems appropriate to separate the whole emission region into two distinct spatial zones, with unique physical properties. The two 'zones' refer to:

1. **Zone 1** - which we will call the 'Hα' zone, refers to all the areas in the nebula where emission is found in all the emission lines, i.e. Hα, [N II], [S II] as well as in [O III]. This zone encompasses all the area within the ellipsoid along the major axis where most of the Hα, [N II] and [S II] emission is located. This zone also extends to the emission along the minor axis (NW and W) to a radius of about 2 pc.

2. **Zone 2** - which we will call the [O III] zone is defined to be the area where features are observed only in [O III]. The second zone is along the minor axis where predominantly [O III] emission occurs. [O III] emission extends in the form of filaments, bubbles or lattice structures beyond the Hα zone extension along the minor axis, up to 4 pc. in radius. This zone also stretches along the shocked outer edge of the entire nebular
emission, i.e. encircling most of Zone 1.

As discussed before, these two zones are significantly different in physical properties and physical parameters. The physical parameters designated to the morphological 'H II' zone - was $T_e = 9000 \, \text{K}$, and $N_e = 400 \, \text{cm}^{-3}$; and for the 'O III' zone a higher $T_e = 36000 \, \text{K}$, and lower $N_e = 10 \, \text{cm}^{-3}$.

The two zones were created by making a binary image of an [OIII]/H$\alpha$ $\lambda\lambda$5007/6563 ratio map, where all the pixels greater than a specified [O III]/H$\alpha$ value were set to 1 ([OIII]/H$\alpha$ > 0.6), and those less than that value were set to 0. The critical value of the ratio was taken to be 0.6. This value was decided on after a careful perusal of the values of the boundaries in the ratio image. Fig. 4.12.a. displays a histogram that shows a section with only 'H$\alpha$' emission from the [O III]/H$\alpha$ ratio image, and Fig. 4.12.b shows a similar histogram of only an [O III] emitting bubble section. We see that the intersection of these two zones lies at around a value 0.6. Therefore the integrated flux was now obtained over two separate zones, and two different physical conditions were used over the two distinct zones. The emissivities $J(5007)$ and $J(80\mu m)$ could now be obtained in the two zones separately, at the $T_e$ relevant to each case.

**INTEGRATED O III SURFACE BRIGHTNESS:**

We estimated the fraction of IRAS observed emission at 60 $\mu$m that is actually contributed by line-emission, in particular the [O III] 52 $\mu$m line, in order to confirm or deny Marsden and Meaburn's (1988) proposed presence of neutral material around NGC 6888. To check if I (52 $\mu$m) emission contributes to the observed IRAS 60 $\mu$m flux, we extrapolated a 52 $\mu$m flux from the observed [O III] $\lambda$5007 integrated flux, from the ratio of the emissivities of these lines, determined using the 5 level atom program. This
calculation was performed for the [O III] and Hα zones separately.

A. O III ZONE:

I. IRAS 60 μm BAND:

For the [O III] zone, a $T_e = 36,000 \, ^\circ K, \, N_e = 10 \, cm^{-3}$ was used.

The value of the emissivities derived using the 5-level atom (De Robertis, Dufour and Hunt) program:

\[
\begin{align*}
  j (5007) & = 1.73 \times 10^{-20} \, \text{ergs} \, cm^{-3} \, s^{-1} \\
  j (52 \, \mu m) & = 6.61 \times 10^{-22} \, \text{ergs} \, cm^{-3} \, s^{-1} \\
  \text{Therefore, } \frac{j (5007)}{j (52 \, \mu m)} & = 26.15
\end{align*}
\]

The calibrated pixels in only the isolated [O III] zone contribute an integrated surface brightness equal to:

\[
I(5007) = 2.76 \times 10^{-10} \, \text{ergs} \, cm^{-2} \, sec^{-1}
\]

Correcting for extinction, assuming an average $c = 0.97$,

\[
I(5007)_{\text{corrected}} = 2.39 \times 10^{-9} \, \text{ergs} \, cm^{-2} \, sec^{-1} \quad \text{and therefore,}
\]

\[
I(52 \, \mu m)_{[O \, III]} = \frac{(3.33 \times 10^{-10})}{26.15} = 9.15 \times 10^{-11} \, \text{ergs} \, cm^{-2} \, sec^{-1}
\]

B. Hα ZONE:

Similarly, the integrated emission contribution was estimated for only the Hα zone, again from the [O III] $\lambda 5007$ image:

\[
I (O \, III)_{H\alpha} = 2.10 \times 10^{-10} \, \text{ergs} \, cm^{-2} \, sec^{-1}
\]

After correcting for reddening:

\[
I(5007)_{H\alpha} = 1.82 \times 10^{-9} \, \text{ergs} \, cm^{-2} \, sec^{-1}
\]

For the Hα Zone, we use a lower value of $T_e = 9000 \, ^\circ K, \, N_e = 400 \, cm^{-3}$,

\[
\begin{align*}
  j(5007) & = 2.130 \times 10^{-21} \, \text{ergs} \, cm^{-3} \, sec^{-1} \\
  j(52) & = 9.899 \times 10^{-22} \, \text{ergs} \, cm^{-3} \, sec^{-1}
\end{align*}
\]
\[ \frac{j(5007)}{j(52)} = 2.15 \]

\[ I(52\mu m) \text{ H}\alpha \text{ zone} = (1.82 \times 10^{-9}) / 2.15 = 8.47 \times 10^{-10} \text{ ergs cm}^{-2} \text{ sec}^{-1} \]

The total contribution of the extrapolated 52 \( \mu m \) emission considering both the zones together gives:

\[ I(52\mu m)_{\text{total}} = I(52)_{\text{H}\alpha \text{ zone}} + I(52)_{\text{OIII zone}} = 9.39 \times 10^{-10} \text{ ergs cm}^{-2} \text{ sec}^{-1} \]

In comparison, the IRAS survey measurement for 60 \( \mu m \) (Van Buren and McCray 1988) gave:

\[ F(60\mu m) = 8.1 \times 10^{-12} \text{ W/M}^2 = 8.1 \times 10^{-9} \text{ ergs cm}^{-2} \text{ sec}^{-1} \]

Therefore the integrated [O III] 52 \( \mu m \) surface brightness - extrapolated from [O III] \( \lambda 5007 \) integrated brightness obtained from the CCD images is only 12\% of the IRAS 60 \( \mu m \) flux recorded.

[N II] 76.5 \( \mu m \):

Morphologically, the IRAS 60 \( \mu m \) image resembles the [O III] \( \lambda 5007 \) image as well as the [N II] \( \lambda 6583 \) image as demonstrated in Fig. 4.10 a, b and c. This is to some extent, due to the fact that the IRAS images are very low resolution, and therefore the filaments and bubbles that distinguish the [O III] \( \lambda 5007 \) image from the others is not noticeable here. The proximity of the [N II] 76.5 \( \mu m \) line to the IRAS 60 \( \mu m \) band encouraged performing a similar calculation for this line as well. In this case though, we used only one zone, as most of the [N II] emission originates in the 'H\alpha' zone, which is a complete recombination zone. An integrated [N II] \( \lambda 6583 \) surface brightness flux was estimated from the CCD image:

Integrated [N II] = \( 5.77 \times 10^{-10} \) ergs cm\(^{-2}\) sec\(^{-1}\)

\[ I \text{ [N II] corrected for redd.} = 2.4 \times 10^{-9} \text{ ergs cm}^{-2} \text{ sec}^{-1} \]

Again from the 5 level atom programme, for \( T_e = 8500 \) K, and \( N_e = 100 \text{ cm}^{-3} \),
\[ j(6583) = 4.76 \times 10^{-21} \text{ ergs cm}^{-3} \text{ sec}^{-1} \]
\[ j(76.5) = 7.40 \times 10^{-29} \text{ ergs cm}^{-3} \text{ sec}^{-1} \]

Therefore, \[ j(5007)/j(76.5 \mu m) = 6.4 \times 10^7 \]

\[ I(76.5 \mu m) = 3.21 \times 10^{-9} / 6.4 \times 10^7 = 3.8 \times 10^{-17} \text{ ergs cm}^{-2} \text{ sec}^{-1} \]

Comparing this to the IRAS 60 \( \mu m \) flux of \[ 8.1 \times 10^{-9} \text{ ergs cm}^{-2} \text{ sec}^{-1} \] concludes that the [N II] 76.5\( \mu m \) line contributes no significant emission to the IRAS 60 \( \mu m \) band flux.

**II. IRAS 100 \( \mu m \) BAND:**

We repeated similar calculations for the IRAS 100 \( \mu m \) band, to see if there is contamination in the observed flux from the [O III] 88.34 \( \mu m \) and/or [N II] 121.8 \( \mu m \) lines:

**[O III] 88.34 \( \mu m \):**

Following the same procedure of separating the [O III] emission region into two distinct zones as before,

In the [O III] zone: \( T_e = 36,000 \text{ K} \), \( N_e = 10 \text{ cm}^{-3} \),

\[ j(5007) = 1.728 \times 10^{-20} \text{ ergs cm}^{-3} \text{ sec}^{-1} \]
\[ j(88.34 \mu m) = 8.995 \times 10^{-22} \text{ ergs cm}^{-3} \text{ sec}^{-1} \], which leads to
\[ j(5007)/j(88.34 \mu m) = 19.21 \]

\[ I(88.34 \mu m) [\text{O III}] = 2.393 \times 10^{-9} / 19.2 = 1.25 \times 10^{-10} \text{ ergs cm}^{-2} \text{ sec}^{-1} \]

In the H\( \alpha \) Zone: \( T_e = 8500 \text{ K} \), \( N_e = 100 \text{ cm}^{-3} \);

\[ j(5007) = 2.13 \times 10^{-21} \text{ ergs cm}^{-3} \text{ sec}^{-1} \]
\[ j(88) = 1.20 \times 10^{-21} \text{ ergs cm}^{-3} \text{ sec}^{-1} \]
\[ j(5007)/j(88) = 1.78 \]
\[ I(88.34) \ H_\alpha = 1.82 \times 10^{-9} / 1.78 = 1.02 \times 10^{-9} \text{ ergs cm}^{-2} \text{ sec}^{-1} \]

\[ I \ (88.34) \text{ total} = 1.25 \times 10^{-10} + 1.02 \times 10^{-9} \text{ ergs cm}^{-2} \text{ sec}^{-1} \]

\[ = 1.145 \times 10^{-9} \text{ ergs cm}^{-2} \text{ sec}^{-1} \]

We note here that the filter band width at 100 \( \mu \text{m} \) is 31.5 \( \mu \text{m} \), which just includes the 88.3 \( \mu \text{m} \) line. Also, the spectral response at 88.3 \( \mu \text{m} \) from Figure 4.7 is about 0.4., giving a corrected contribution of:

\[ I \ (88.34\mu\text{m})\text{total} = 4.58 \times 10^{-10} \text{ ergs cm}^{-2} \text{ sec}^{-1}. \]

\[ \text{[N II] 121.8 }\mu\text{m:} \]

Also, at \( T_e = 8500 \ ^\circ\text{K}, \ N_e =100 \ \text{cm}^{-3} \), the [N II] 121.8 \( \mu \text{m} \) emissivity:

\[ j(6583) = 4.76 \times 10^{-21} \text{ ergs cm}^{-3} \text{ sec}^{-1} \]

\[ j \ (121.8\mu\text{m}) = 2.99 \times 10^{-22} \text{ ergs cm}^{-3} \text{ sec}^{-1} \]

\[ j \ (5007) / j \ (121.8) = 15.93 \]

\[ I(121.8\mu\text{m})=3.21 \times 10^{-9}/15.93 \text{ ergs cm}^{-2} \text{ sec}^{-1}= 2.01\times10^{-10} \text{ erg cm}^{-2}\text{sec}^{-1} \]

Again, although the 100 \( \mu \text{m} \) band has a bandwidth of 31.5 \( \mu \text{m} \), the system spectral response at 122 \( \mu \text{m} \) is about 0.35. Therefore, after correcting for this term

\[ I \ (121.8) = 7.04 \times 10^{-11} \text{ ergs cm}^{-2} \text{ sec}^{-1} \]

From the IRAS survey:

\[ F_{100} \ (\text{W/M}^2) = 1.7 \times 10^{-12} \text{ W/M}^2 = 1.7 \times 10^{-9} \text{ ergs cm}^{-2} \text{ sec}^{-1} \]

From the above, we conclude that [O III] 88.34 \( \mu \text{m} \) (27%) and to a smaller extent [N II] 121.8 \( \mu \text{m} \) (5%) contribute relatively little to the IRAS 100 \( \mu \text{m} \) emission.

We have thus shown that the contribution to the IRAS observed 60 \( \mu \text{m} \) and
100 \, \mu m \, flux, from the line emission ([O III] 52\,\mu m, [N II] 76.5\,\mu m, [O III] 83.4 \, \mu m and [N II] 121.8 \, \mu m) is less than 30\%. Marsden and Meaburn (1988), assuming a worst case line emission of 30\% had concluded that about 90\% of the total shell mass was constituted of neutral material, and only 10\% of ionized material. Our extrapolations from our [O III] and [N II] emission lines in the visible to the IR has ascertained that the emission-line contributions to the observed IRAS fluxes is less than 30\%. This supports Marsden and Meaburn's proposal of a neutral shell around the ionized shell, thus implying that the total mass of the shell is in fact \sim 40 \, M_\odot, and that the mass of the ionized gas is only 5 \, M_\odot. The low filling factor derived previously also suggests this.

IV.5. NEUTRAL MASS:

For wind-driven bubbles around WR stars it is likely that the ionized mass \( m_i \) is less than the shell mass \( m_s \), since the ionization front does not necessarily coincide with the shell's outer radiative shock. When the ionization front is interior to the shell, a significant part of the shell remains neutral and therefore undetected optically, and the ionization front is 'trapped'. In such a case \( m_s \) is underestimated, and the corresponding values of \( \epsilon_s \) and \( \pi_s \) obtained, the energy and momentum efficiency parameters (defined later) are smaller than the correct values.

Van Buren (1986) suggested that pressure in the shell can be measured using shell diagnostics, using the conservation equations for the dynamics of the swept-up shell of a stellar wind bubble expanding with a velocity \( v_s \) into a medium of density \( \rho_0 \). This gives the mass of the shell if the radius of the bubble is known, assuming there are no density inhomogeneities. The shell mass derived in this way includes the visible ionized portion of the shell, as well as any exterior neutral component that may remain undetected. The ambient density is then given by the equation (Van Buren 1986):
\[
n_0 = \frac{5 n_s k T_s}{2 \mu_H m_H v_s^2} = 2.06 \times 10^2 n_s T_{s,4} v_{s,5}^{-2} \mu_H^{-1} \text{ cm}^{-3}
\]

(4.10)

Where \( n_0 \) is the exterior number density and all the quantities on the right-hand side are parameters measured in the ionized part of the shell. \( T_{s,4} = T_e / 10^4 \) is the shell temperature, \( v_{s,5} \) is the expansion velocity in km s\(^{-1}\), and \( \mu_H \) is the mean molecular weight per hydrogen atom. The mass of the shell is therefore given by:

\[
m_s = \left(\frac{4 \pi}{3}\right) r_s^3 n_0 m_H \mu_H
\]

(4.13)

\[
= 4.21 \times 10^{34} r_s^{3, \text{pc}} n_s T_{s,4} v_{s,5}^{-2} \text{ g}
\]

Using eqn. 4.10 and 4.11 we get \( n_0 = 8 \text{ cm}^{-3} \), and from this value of the ambient density we get \( m_s = 20 M_\odot \). Van Buren derived a higher value for the ambient density \( (n_0 = 25 \text{ cm}^{-3}) \); and used \( n_s = 1000 \text{ cm}^{-3} \) for NGC 6888, resulting in a value of \( m_s = 65 M_\odot \).

This result is in agreement with the mass obtained from IRAS data in the last section. Therefore, the mass of the NGC 6888 shell is in the range 20-60 \( M_\odot \). We will thus adopt a value of 40 \( M_\odot \) for further calculations. As the total shell mass \( (\sim 20 - 60 \text{ M}_\odot) \) is thus found to be much greater than that of the ionized mass \( (5 \text{ M}_\odot) \), this suggests that the neutral shell exists outside the ionized material, which is the observed shell.

The above calculation also suggests that most of the neutral shell mass can be created by swept-up ambient material, also noting that the ambient density around NGC 6888 is unusually high \( (\sim 8 \text{ cm}^{-3}) \) compared to that around Galactic H II regions. This indicates that the shell contains neutral material, and there are ionization fronts trapped
interior to the neutral material. If $S$ is the stellar continuum photon luminosity and $R$ is the number of recombinations per second in the shell assuming complete ionization, a dimensionless parameter $l = S / R$ indicates quantitatively if the shell is completely ionized (Van Buren 1986):

$$l = \frac{S}{\left( \frac{m_s}{m_H n_s} \right)} = 3.21 \times 10^4 S_{49} m_{s,0}^{-1} n_s^{-1} \mu_H$$

(4.14)

In section IV.2.b.II we obtained $S_{\text{LyC}} = 0.045 \times 10^{49}$ photons s$^{-1}$, from the value of our integrated H$\alpha$ flux. Using this value of $S_{\text{LyC}}$ and $m_s = 20 \ M_\odot$, $l = 0.29$. This affirms that trapped ionization zones exist in the shell of NGC 6888.

IV.6. MASS COMPONENTS OF THE NEBULA:

At this point we have reasonable mass estimates for the ionized and the neutral parts of NGC 6888. From the N and He enrichment observed we had earlier speculated on the possibility of stellar ejecta constituting part of the nebular make-up. In the following sections we evaluate the N and He enrichment contributed by the central star, and other components that constitute the mass of the nebula. The question to be addressed is whether NGC 6888 (at least the ionized part) consists of wind-swept ISM, or actual stellar ejecta or parts of both.

i). Mass loss due to wind?

Barlow, Smith and Willis (1981) estimated the mass loss of HD 192163 from measurement of infrared free-free fluxes to be
\[ \frac{dM}{dt} = 2.3 \times 10^{-5} \, M_\odot \, \text{yr}^{-1} \]

Over the dynamical lifetime of the nebula therefore, the total mass due to the wind loss from the star is

\[ \frac{dM}{dt} \times t \, (\text{yr}) = (2.0 \times 10^4) \times (2.45 \times 10^{-5}) \, M_\odot = 0.5 \, M_\odot \]

This suggests that since the formation of NGC 6888, the current stellar wind has contributed only a few percent of the total ionized mass.

ii). **Enriched Mass:**

The abundance calculations shown in the previous chapter have already indicated that the shell is enriched in N and He, in comparison to galactic H II regions. It is useful to consider if the N and He enrichment derived for the knots of NGC 6888 could be the sole result of wind enrichment of normal composition ISM material, or must the knots be processed stellar ejecta. The latter can be confirmed from the stellar spectra. Willis and Wilson (1978) have derived the abundances in Wolf-Rayet stars, including HD 192163 from ultraviolet spectral observations. We can therefore estimate the contribution of the star to the enrichment of the shell knowing the abundances in the shell as well as in the ambient interstellar medium. We consider the fraction \( f^* \) of nebular material contributed by the stellar wind, where \( f^* \) is defined as:

\[
f^* = \frac{A_{\text{neb}} - A_{\text{ISM}}}{A^* - A_{\text{ISM}}}
\]

(4.15)

\( A_{\text{neb}} \) gives the ratio of any two elemental abundances in the star, \( A^* \) gives the same ratio in the star, and \( A_{\text{ISM}} \) gives the same ratio in the ISM.

Smith (1973) showed that hydrogen is extremely deficient in the WN atmospheres. Therefore all the abundances are given relative to He. The N/He abundance
by mass in the star is given to be $3.5 \times 10^{-2}$ for 30,000 °K stellar temperature and $4.7 \times 10^{-2}$ for 40,000 °K stellar temperature. As the temperature is uncertain, the N/He abundance in the star is taken to be $4.1 \times 10^{-2}$ by mass. This gives a N/He abundance of 0.012 by number. For the N/He abundance in the ISM we adopt the value of Orion (Peimbert & Torres-Peimbert 1977) which equals $3.6 \times 10^{-4}$. For the nebula, we consider two positions, (1) NE - which has an average abundance of N/He = $1.0 \times 10^{-3}$, and (2) NO3-60W - which has one of the higher values of N/He = $2.2 \times 10^{-3}$. Using the above values in eqn. 4.13, we get:

<table>
<thead>
<tr>
<th></th>
<th>NE</th>
<th>NO3-60W</th>
</tr>
</thead>
<tbody>
<tr>
<td>$f^*$</td>
<td>0.05</td>
<td>0.16</td>
</tr>
</tbody>
</table>

From our earlier estimate of the total mass of the shell to be 20 - 60 $M_\odot$ we get total mass of enriched material contributed by the star:

$$M_{enriched} = 1 \ M_\odot - 3 \ M_\odot \quad 3.2 \ M_\odot - 9.6 \ M_\odot$$

The value of the enriched (ionized) mass in the nebula is several times higher than the mass lost by the stellar wind over the dynamical lifetime of the nebula. This suggests the existence of ejecta besides that which is contributed by the stellar wind; even pointing towards the possibility of a previous ejection phase of the star.

However, this enriched material constitutes only on the order of 10% of the nebular mass. This suggests that the majority of the mass in the neutral shell probably comes from the swept up interstellar material during nebular expansion, as discussed before. This indicates that the density in the ambient medium must be unusually high, which is what we derived earlier, in section 4.4. This may be because the nebula is enclosed inside an extended common shell swept up by the stars of Cyg OB1, i.e. interior to the Cygnus superbubble (Lozinskaya and Sitnik 1988), or due to the presence of molecular clouds in the region as seen in IRAS data (Marsden and Meaburn 1988).
IV.7. **ENERGY VS. MOMENTUM CONSERVATION**

The energy efficiency parameter $\varepsilon_s$ is defined to be the ratio of the observed kinetic energy of the shell to the total kinetic energy emitted by the wind since the formation of the shell (Marsden and Meaburn 1988, Treffers and Chu 1982):

\begin{equation}
\varepsilon_s = \frac{M_s V_s^2}{M_w V_w^2 t}
\end{equation}

and $\pi_s$, the momentum efficiency is the ratio of the current shell momentum to the total injected wind momentum:

\begin{equation}
\pi_s = \frac{M_s V_s}{M_w V_w t}
\end{equation}

Here $M_s$ is the mass of the shell, $V_s$ is the shell velocity, $V_w$ is the terminal wind velocity and $M_w$ is the mass loss rate. For energy driven bubbles, $\varepsilon_s$ is predicted to be 0.2 with $\pi_s \sim 1$. In a momentum driven flow predicted values are $\varepsilon_s \ll 1$ and $\pi_s \sim 1$.

First, calculating these parameters with only the value of the ionized mass, $M_s = 10 M_\odot$, and using $V_s = 85 \text{ Km s}^{-1}$ (Marsden and Meaburn 1988), $M_w = 2.45 \times 10^{-5} M_\odot$ and $t = 2.0 \times 10^4 \text{ yr}$, we find

$\varepsilon_s = 0.026$

and $\pi_s = 0.733$

These values compare more to a momentum conserving, rather than an energy conserving bubble, similar to the results of Treffers and Chu (1982).

We note that there could be several sources of errors in the derivation of these parameters. The possibilities include the existence of neutral material in the shell that is
too cool to emit detectable optical or radio emission, which is likely to be the case here. Mass could be hidden in cool material if the ionization front is trapped within the shell. The increase in mass by such a significant amount could make all the difference in $\varepsilon_s$ and $\pi_s$, and could change it to an energy conserving case similar to the scenario suggested by Marsden and Meaburn. In this case ionization fronts would be existing in the shell.

Other sources of errors in these parameters is the variability of the stellar wind over the lifetime of the star. However, the lifetime of the WR phase is thought to be a few times $10^5$ years (Chiosi, Nasi and Sreenivasan 1978) and the mass loss rates of most of the WR stars are comparable. Since this is a relatively young shell, variability of the wind should not be a significant source of error.

An increased value of $M_s$, i.e. $M_s = 40 M_\odot$ to account for the neutral mass also present results in new values for the efficiency parameters of :

$$\varepsilon_s = 0.18 \quad \text{and} \quad \pi_s = 5.6.$$  

Calculations for the dynamic situation of a stellar wind interacting with ambient ISM/ejecta show (Weaver et al 1977), that for the energy conserving phase of the bubble approximately 60% of the stellar wind energy goes into the internal energy of the gas, 20% into the kinetic energy of the shell, and 20% is radiated away by the outer isothermal shock. This indicates that $\varepsilon_s$ for an energy conserving bubble should be $\sim 0.2$. The close match with our results strongly suggest that NGC 6888 falls into the energy conserving case, rather than momentum conserving, assuming that the expansion of the shell is driven by the wind from the central star.

We note that the preceding calculations assume that the shell in NGC 6888 is a classic wind-blown bubble, i.e. wind plowing into ambient medium. In this case the dynamics are actually far more complicated because of the mixing of stellar ejecta with the stellar wind, when the bubble was formed. The shell energy and momentum measured
therefore contain contributions from the stellar ejecta present in the wind-blown bubble, and therefore the efficiency parameters are almost certainly being overestimated. As the initial energy and momentum of the ejecta is unknown, it is not possible to accurately predict these parameters for the NGC 6888 'wind-blown' bubble.

IV.8. 'KNOT' STRUCTURES

Our imagery shows more detailed structure in the nebula compared to previous studies, especially of the system of bright condensations that were referred to previously as 'knots'. It is therefore advantageous to study in detail the physical properties of these knots, as 'knot' or filament like structures could be the end results of instabilities or interactions of the shell with the ISM.

a) Linear Dimensions:

First, the measurements of knot sizes is discussed. To measure the lengths of the knots accurately, we first had to determine the 'seeing' limits on our resolution. We did this by taking one-dimensional slices across several stars, and measuring the width of the gaussians to determine the point-spread function. The point-spread function describes the resulting spread or profile in the image plane, of a point source that is smeared out due to diffraction, aberrations, seeing, etc. Our average FWHM for the width of about 12 stars was about $2.00 \pm 0.15$ pixels, and the corresponding point spread function of the star, $\sigma^* = 0.74 \pm 0.06$ pix = 0.8". Similarly, one-dimensional slices were taken along the middle of the knots, along the horizontal and vertical axes. Gaussians were fitted along the width of these knots in the slices. In this way the FWHM and the corresponding $\sigma_{\text{knot}}$ for the length and breadth of several representative knots in the different regions (NE, NW, W and S) were obtained. An example of this procedure is
shown in Fig. 4.14.

These measurements were then corrected for the effects of seeing using the following:

\[
(\sigma_{\text{obs.}})^2 = (\sigma_{\text{true}})^2 + (\sigma_*)^2
\]  \hspace{1cm} (4.18)

Where \( \sigma_{\text{obs.}} \) is the measured width of the knot, \( \sigma_* \) is the point spread function of the star, and \( \sigma_{\text{true}} \) is the actual width of the knot after the 'seeing' correction. This method was used to determine both the length and breadth of the knot. After determining the surface area of the knot i.e. \( \sigma_{\text{length}} \times \sigma_{\text{breadth}} \), the whole knot was approximated to be a square, and the length of the square was taken to be the linear dimension of the knot.

The lengths of the knots are included in Table 4.6. We note that most of these knots have lengths close to 5 pixels, or \( 6.5'' = 0.046 \text{ pc} \). The uniformity of the length in all these knots is an indication that these knots have a common physical nature, and this is discussed in the following sections.

ii) **Filling Factor**

The filling factor and mass were calculated for the individual knots, using individual \( N_e \)'s calculated in the last Chapter for each of the knots. For \( N \text{ rms, H}\beta \text{ fluxes} \) integrated over the area of each knot was used for the \( I(\text{H}\beta) \) term, and the length of the knot \( (r) \) as in the last section. A mean value of \( N_p = 0.18 \) was used for all the knots, where \( N_p \) is the proton rms density \( (= 1 + \text{He}^+/\text{H}^+ + \text{He}^{++}/\text{H}^+) \). Eqn. 4.7 and 4.8 were used for the calculation of the individual filling factor \( \gamma \)'s for all the knots, and this is presented in Table 4.6. Eqn. 4.12. was used to estimate masses of the individual knots, from their filling factors. We assume that the knots are spherical, with radius as shown in Table 4.6. The volume of each knot was therefore taken to be \( V_{\text{knot}} = 4/3\pi (R_{\text{knot}})^3 \). The filling factors calculated for each of the knots was used to calculate the emitting
volume for eqn. 4.9. The shell thickness dR was taken to be 0.1 pc (Wendker et al. 1975).

<table>
<thead>
<tr>
<th>Posn.</th>
<th>I(Hβ) (x10^{-13})</th>
<th>R knot</th>
<th>N_e (rms)</th>
<th>N_e (FL)</th>
<th>F.F.</th>
<th>M (M_⊙)(x10^{-4})</th>
</tr>
</thead>
<tbody>
<tr>
<td>NE2-W</td>
<td>4.34</td>
<td>6.24''</td>
<td>123.1</td>
<td>300</td>
<td>0.17</td>
<td>2.42</td>
</tr>
<tr>
<td>NW2-W</td>
<td>6.86</td>
<td>6.85''</td>
<td>128</td>
<td>600</td>
<td>0.05</td>
<td>1.67</td>
</tr>
<tr>
<td>NW1-W</td>
<td>5.29</td>
<td>6.26''</td>
<td>136</td>
<td>600</td>
<td>0.05</td>
<td>1.47</td>
</tr>
<tr>
<td>SO3-W</td>
<td>4.16</td>
<td>6.29</td>
<td>121</td>
<td>150</td>
<td>0.64</td>
<td>4.64</td>
</tr>
</tbody>
</table>

As a check on the mass estimates of these knots, we can reverse this calculation and estimate the mass of the shell from the mass of the knots. We assume that the knots are cylindrical and that the height of the cylinder, i.e. the thickness of the knots runs through the whole visible shell thickness, which is the ionized mass. With these assumptions, the fraction of the shell volume that is occupied by one knot of average dimensions, and average filling factor is:

$$\frac{\text{Vol} \ (\text{Knot})}{\text{Vol} \ (\text{Emmiting Shell})} = \frac{\frac{4}{3} \pi r_{\text{knot}}^3}{\frac{4\pi}{3} \int_{r_{\text{shell}}}^r r^2 dr} = \frac{\frac{4}{3} \pi (6.2'')^3}{\frac{4\pi}{3} \times 14.2''} = 3.3 \times 10^{-5}$$

Therefore the mass of the ionized shell is:

$$\text{Mass} \ (\text{Shell}) = \text{Mass} \ (\text{Knot}) \times \frac{\text{vol} \ (\text{Shell})}{\text{vol} \ (\text{knot})} = \frac{2.4 \times 10^{-4}}{3.3 \times 10^{-5}} = 4.4 M_⊙$$

This is approximately the mass of the visible part of the shell; note we had
calculated the mass of the visible part of the shell originally to be around $5 \, M_\odot$. The rest of the mass is located in a neutral shell located exterior to the observed ionized shell, which was previously identified using IRAS observations.

IV.8.b. **Origin of 'Knots'**

The knots are defined to be clumps or condensations that are brighter than the immediate surroundings. Morphologically, they resemble clumps found in stellar ejecta type nebulae such as RCW 58 (Chu 1981) and M1-67 (Chu and Treffers 1981) and knots found in supernova remnants such as Cas A (Chevalier 1975). Possible mechanisms that can create knots of this nature are:

1. Matter that was previously ejected from the star in a peculiar manner (Pismis *et al.* 1977).

2. Density inhomogeneities that existed in the surrounding ISM which were swept up by the wind or stellar ejecta and now exist interior to the bubble.

3. As a result of instabilities in the shell, such as Rayleigh-Taylor instabilities that are created as a result of mixing of media of different densities.

The N and He enrichment observed in the knots suggests that stellar ejecta is a possibility. Calculations investigating the possibility of Rayleigh-Taylor instabilities as the formation mechanism for the knots are discussed below.

A knot pushing into the ambient medium is retarded by the ram pressure exerted on it by the ambient medium. Assuming the knots are spherical, at a stopping distance $D_s$, the mass swept up by the outward motion of the knot is assumed to be equal to the mass of the knot and is given by:

\[
\text{Mass swept up} = \text{Mass of knot} = \frac{4}{3} \pi R_k^3 \rho_k \quad \text{Or,} \quad (\pi R_k^2 \rho_A D_s = \rho_k 4/3 \pi R_k^3)
\]  

(4.19)
where \( D_s \) is defined to be the 'stopping distance', i.e. the distance at which the knot comes to rest. \( \rho_A \) and \( \rho_K \) are the densities of the ambient medium and the knots respectively, and \( R_k \) is the size of the knot, or in this case the radius. The stopping distance \( D_s \) is therefore given by

\[
D_s = (\rho_K / \rho_A) \times R_k
\]

(4.20)

The associated stopping time \( t_s \) which is a measure of the lifetime of the knot before it comes to rest is given by

\[
t_s = D_s / v_k \sim (\rho_K / \rho_A) \times R_k / v_k
\]

(4.21)

Adopting \( R_k = 6.5'' \) from Table 4.6, and \( \rho_K = 400 \text{ cm}^{-3} \), \( v_k = 85 \text{ km s}^{-1} \) and \( \rho_A = 10 \text{ cm}^{-3} \) (from previous sections) for the knots in NGC 6888, the above equations give :

\[
D_s = 260''
\]

\[
t_s \sim 2 \times 10^4 \text{ yr}
\]

We note that the stopping time calculated for the knots is similar to the dynamic lifetime of the nebula \( \sim 2 \times 10^4 \text{ yr} \). This indicates that the shell is currently in a decelerating phase, which implies that the observed expansion velocity of the shell \( \sim 85 \text{ km s}^{-1} \) is much less than the original expansion velocity. A lower expansion velocity also implies that the 'true' dynamical age of the nebula is less than that previously estimated \( \sim 2 \times 10^4 \text{ yrs.} \)

The deceleration associated with the stopping time \( t_s \) :

\[
- g = v_k / t_s
\]

(4.22)

Using \( v_k = 85 \text{ km s}^{-1} \) which is the observed velocity for the knot,

\[
- g = 1.3 \times 10^{-5} \text{ cm s}^{-2}
\]

We now consider the possibility that the knots are created due to Rayleigh-Taylor instabilities, which seems plausible as in the given case a higher density medium is moving into a lower density medium. The growing time of such instabilities is
\[ t_g = \sqrt{\frac{\lambda}{2 \pi g}} \]

where \( \lambda \) is the wavelength of the instability (Blake, 1974). Assuming the wavelength of the instability is similar to the size of the knot, we use \( \lambda = 6.5" = 1.4 \times 10^{17} \text{ cm} \) and the deceleration \( g \) as derived previously:

\[ t_g = 1300 \text{ yrs.} \]

Our calculations show that \( t_g << t_s \). This implies that the knots are bound to break up and that Rayleigh Taylor instabilities are the most plausible mechanisms for the formation of the knots, and could have occurred during the dynamical lifetime of the nebula.

IV.8.c. Evolution of the 'Knots'

Possible sources of formation of the knots was discussed in the last section. In this section we consider the physical processes that could be maintaining the knots in their observed situation.

As the density of the knots (~400 \text{ cm}^{-3}) is higher than the density of the ambient medium (10 \text{ cm}^{-3}) (assuming a \( T_e = 10^4 \text{ K} \)), the internal pressure of the knots is higher than that in the ISM. In the absence of any other confining media (for example, a surrounding wind-blown bubble) the knots would tend to expand. The current emission measure EM in the knots is about 8000 \text{ cm}^{-6} \text{ pc}, for a density = 400 \text{ cm}^{-3} and a diameter of 0.1 \text{ pc}. In the absence of an enclosing bubble, the diameter would have to triple for the knot to fall below the Palomar Sky Survey detection limit of \( \text{EM} = 50 \text{ cm}^{-6} \text{ pc}. \) The sound crossing time for the expanded knot would be \( 2.4 \times 10^3 \text{ yrs} \), indicating that if the knots were placed directly in the ambient ISM, they would have fallen below the detection limit in only \( 2 \times 10^3 \text{ yrs} \). (hereafter referred to as the 'dissipation time'.) The fact that the knots are still visible indicates that the knots are being constrained either by the wind blown
bubble observed around the shell, or the ram pressure on the knots by the surrounding medium.

If the knots are located interior to a wind-blown bubble as suggested, the expansion of the knots would be constrained as the opposing pressure would now be that interior to the bubble. In this case, the destruction of the knot may take place because of heat conduction on the surface leading to evaporation. The characteristic time for cloud evaporation is given by Cowie and McKee 1977:

\[ T_{\text{evap}} = 3.3 \times 10^{20} n_c R_{pc}^2 T_f^{-5/2} \ln \frac{\Lambda}{30} \text{ yr} \]

(4.24)

Where \( n_c \) is the mean hydrogen density of the knot, \( R_{pc} \) is the radius of the knot in parsecs, and \( T_f \) is the temperature of the surrounding medium at a point away from the knot. If we consider the wind blown bubble as the surrounding medium, i.e. \( T_f = 10^7 \text{ K} \) in eqn. 4.22, a value of \( T_{\text{evap}} = 10^3 \text{ yrs} \) is obtained, which is an order of magnitude shorter than the dynamical lifetime. We note that \( T_{\text{evap}} \) in this case is comparable to the growing time of the Rayleigh Taylor instability that was derived from eqn. 4.21. This suggests that a continuous parallel process consisting of creation of the knots by Rayleigh-Taylor instabilities and destruction by evaporation may be taking place. On the other hand, a lower value of \( T_f \) for the surrounding medium would give a more reasonable value of \( T_{\text{evap}} \). This suggests that the knots may actually be located in a cooler medium such as the actual diffuse nebular part consisting of the ejecta as well as swept-up ambient medium, and not directly in the wind-blown bubble. The CCD images also visually indicate that the knots are located in the diffuse nebular H\alpha shell.

The dissipation time in the absence of a wind (2.4 \( \times 10^3 \text{ yrs} \)) had suggested confinement of the knots. The evaporation time calculated indicates that the knots are
actually confined not by the wind blown bubble but a cooler medium. An alternate source of confinement of the knots may be the ram pressure of the ambient medium.

The ram pressure on the knots by the ambient medium is given by:

$$ P_{\text{ram}} = \rho_A v_k^2 $$

(4.25)

Using $\rho_A = 10 \text{ cm}^{-3}$ as the ambient density, and $v_k = 85 \text{ km s}^{-1}$ gives a ram pressure equalling $1.0 \times 10^{-8} \text{ g cm}^{-1} \text{ s}^{-2}$. On the other hand, the pressure interior to the knot is

$$ P_{\text{knot}} = \rho_k k T_e $$

Using previously used values, $P_{\text{knot}} = 5.5 \times 10^{-10} \text{ g cm}^{-1} \text{ s}^{-2}$. This indicates that the ram pressure due to the ambient medium is greater than the pressure interior to the knots by a factor of $\sim 20$, and is also a plausible confining mechanism.

IV.9. COMPARISON OF THIS STUDY WITH OTHER OBSERVATIONS

IV.9.a. Radio Measurements

Radio observations of NGC 6888 were made by Johnson and Hogg in 1965, and Wendker et al in 1975. Wendker et al (1975) presented H$\alpha$ + [N II] isophotes, and 6 cm., 21 cm. and 49 cm. continuum isophotes. The extent of the emitting regions is found to be similar in the two cases. However, the brightness isophotes do not appear to be identical. They also found the radio radiation to be completely thermal in nature, i.e. probably brehmsstrahlung. They concluded that the non-thermal contribution was minimal; at 600 MHz $< 0.3 \times 10^{-26} \text{ W m}^{-2} \text{ Hz}^{-1}$.

From our CCD imagery, the observed integrated H$\alpha$ flux was estimated to be $= 3.2 \times 10^{-9} \text{ ergs cm}^{-2} \text{ sec}^{-1}$. The volume emissivities at 1400 MHz and H$\alpha$ are related by (Oster 1961):

$$ j(1400) = 4 \times 10^{-15} j(\text{H}\alpha) $$
Therefore, the observed value of Hα flux leads to an expected $S(1400) = 1.3 \times 10^{-26}$ W/m² Hz. Lozinskaya (1970) gives the observed $F_{1400} = (4.7 \pm 1.0) \times 10^{-26}$ W/m² Hz. This agrees quite well within observational constraints.

Lozinskaya (1970) affirmed that the radio source connected with NGC 6888 was thermal, with a spectral index $\alpha \sim -0.15 \pm 0.07$. (Lozinskaya 1970). She also discusses that there is no physical difference between the smooth component and the filaments, in terms of $N_e$ and $T_e$.

IV.9.b. X-RAY EMISSION FROM NGC 6888

X-rays from NGC 6888 was not detected by Exosat (Kahler et al. 1987). On the other hand, the flux was observed at the IPC detectability level of the Einstein Observatory in 1979 (Bochkarev 1988). This was the first direct proof that wind blown bubbles are filled by hot wind (Bochkarev et al. 1987). Four X-ray sources were found in a 1° x 1° field centered on HD 192163, two of which were point-like components and two were extended. Table 4.7 gives the coordinates, the signal and the value of the observed flux for each of the sources. The X-ray spectrum recorded could be approximated by thermal radiation of plasma with a temperature $kT = 0.65$-0.8 kev with a weaker low-frequency decline ($N_H < 10^{21}$ cm⁻²), than should follow from the color excess of the central star ($E_{B-V} = 0.5 - 0.6$, $N_H = 3 \times 10^{21}$ cm⁻²) (Lozinskaya 1988). This difference of $N_H$ may signify the presence of dust in the outer layers of the star's atmosphere or inside the hot wind region. No emission was noted from the central star HD 192163. The calculated spectral form suggested that the interaction of the stellar wind of the central star with the interstellar medium was the dominant source of X-rays from the nebula (Bochkarev 1988).

Weaver et al. (1977) suggest that in the snowplow phase, the hot, shocked
stellar wind region interior to the shell (Region b) emits bremsstrahlung with luminosity:

\[ L_b = 3.8 \times 10^{33} n_0^{18/35} (M_6 V_{2000}^2)^{37/35} t_6^{16/35} \text{ ergs s}^{-1} \]  \hspace{1cm} (4.26)

where \( M_6 = M_w / 10^6 M_\odot \) yr\(^{-1} \), \( V_{2000} = V/2000 \) km s\(^{-1} \), and \( t_6 = t / 10^6 \) yrs. For NGC 6888, this gives \( \sim 3 \times 10^{28} \) ergs s\(^{-1} \), or a flux \( F_x = 1-3 \times 10^{-11} \) ergs cm\(^{-2} \) s\(^{-1} \). The measured X-ray flux from the Einstein Observatory (Bochkarev 1988) was only found to be \( F_x = 10^{-12} \) ergs cm\(^{-2} \) s\(^{-1} \). The observed X-ray luminosity was therefore found to be an order of magnitude less than that given by the models of Weaver et al. (1977). Bochkarev explained this by leakage of a significant fraction of stellar wind through interstellar medium inhomogeneities (i.e. filaments?); visually the nebula definitely appears to show signs of such leakage in the form of the [O III] bubbles. An alternate explanation given by Lozinskaya (1988) is that by analogy with SNR's there could be loss of hot wind energy by dust collision and radiation of warm dust in the IR that prevail over the cooling by radiation of hot gas. i.e. The object could be young enough that ionization equilibrium has not yet been established.

Of course, as discussed previously, the classical wind-blown bubble case is not valid here, as the energetics are controlled by both the stellar wind, and that of the stellar ejecta that is mixed in. A classical bubble assumption therefore, overestimates the energy in the wind, and consequently the predicted X-ray emission is overestimated.

We note from Table 4.7 that source 2 is centered on a position that encompasses the NE and NW part of the optical part of the nebula, though it is more offset towards the NE. Source 3 is centered on our 'S' region. Fig. 4.15 shows an optical image of NGC 6888, with the X-ray image superposed on it. This figure shows that the two X-ray sources in the 0.2-3.5 KeV energy range fit into diametrically opposite regions of the envelope along the major of the nebula, indicating that the ejecta is denser
along the equatorial plane. The X-ray image, therefore corroborates the idea of bi-polar stellar wind or bipolar shell ejection, as discussed before.

IV.9.c. The velocity Structure

It is important to understand the velocity structure and geometry of this nebula, so that ionization and composition in various regions can be mapped as a function of true distance from the star, and not just the projected distance as has been done so far.

Recent radial velocity studies of this object include Fabry Perot observations in Hα and [O III] λ5007 by Treffers and Chu (1982) and echelle spectrophotometry by Marston and Meaburn (1988). These studies concluded that the presence of two velocity components in some of the positions, and three components in many of the positions observed suggested a bubble of ionized gas expanding radially. The positive and negative components correspond to the approaching and receding part of the nebula, and the central part corresponds to the ionized material along the line of sight, probably originating in the surrounding Cyg. OB1 bubble around NGC 6888. Marsden and Meaburn fitted this data with a velocity ellipse that suggested an expansion velocity of 85 km s⁻¹, and a radius of 420'' = 2.95 pc for the expanding bubble.

More recently, Lozinskaya (1988) studied NGC 6888 with Fabry Perot interferometry in the [O III] λ5007. After attempting to fit the radial velocity data with three different configurations of expanding shells, Lozinskaya concluded that the best fit was obtained for a prolate ellipsoidal shell, which is inclined to the plane of the sky by an angle φ = 20°- 40°, assuming a constant expansion of velocity (88 km s⁻¹). The line profile of the [O III] line also suggested that [O III] originates in a thin, regularly expanding hollow envelope.

To understand the geometry of specific features further, I marked the
positions of some of the knots discussed in my study, on the Hα spectral grid as obtained by Treffers and Chu. This is shown in Fig 4.16, and shows a grid of observations that were centered on the star, and separated by 2' each. The noteworthy points from this figure are:

1. The positions of the NE and the SW knots appear to be equidistant from the star, at least along the 2-D representation. This figure shows the axis joining NE-SW is about 16" while the axis joining NW to SE (measured perpendicular to the previous axis) is measured to be only about 10.5". The end-points of these assumed axes are marked on the plot. The inequality in the major and minor axis suggests that the nebular shell is elliptical, and not spherical. It seems likely that the observed projected morphology which appears to be an ellipse, is in reality a cross section of the ellipsoid along the major axis, and NE and SW appear to lie at the ends of the major axis.

This again points to the nebula being bipolar in it's geometry and may explain why NE and SW nebular regions are physically similar. NE and SW being located at identical distances from the central star, suggests a common origin, and similar physical processes at these two positions.

Possible reasons for the asymmetric shape of the bubble are:

(a). Asymmetric ejection by the star originally, which could be the result of a rotating star.

(b). Due to non-uniform distribution of the ambient medium into which the nebula is expanding. This seems to be the most plausible reason as the nebula is located inside a superbubble formed by the Cygnus OB1 association. IRAS observations also indicate the presence of molecular clouds in that region (Marsden and Meaburn 1988).

(c). Due to the location of NGC 6888 inside a magnetic field. This possibility was considered by Lozinskaya (1970), where she showed that the direction of the
projection of the major axis of the nebula also coincides with the direction in which the nearest diffuse nebulae are elongated. On the contrary, Falle (1975) showed that the distortion produced by an ambient magnetic field in the ISM on the shape of a spherical nebula is insignificant. Of note, though is that they used a spherically symmetric field; a field that is not spherically symmetric would produce a larger distortion.

(d). Asymmetry in the stellar wind. This seems an unlikely cause if bubble theory (Weaver et al. 1977) applies to the dynamics of this nebula, as the high pressure region is supposed to be nearly isobaric. On the other hand, the bipolar lobes found in the X-ray emission attests to asymmetric stellar wind along the major axis.

2. The positions in the northern half of the nebula, and especially the NE region demonstrate brighter negative components, as shown in Fig.4.16. The intensity of positive components increase towards the SW, along the major axis.

This implies that the ellipsoid is tilted such that the NE is inclined towards the observer. This could explain why the approaching gas in the NE is brighter. Adopting the value for the inclination that was determined by Lozinskaya's model, suggests that the nebula is an ellipsoidal shell with the NE edge inclined at 20-40° to the plane of the sky, towards the observer.

We note that the bright knots we had labelled 'E' and 'SO3' also show brighter negative components of velocity, as marked in Fig.4.16. This indicates that both these features are approaching the observer. The trailing filament associated with E may be caused by dense clouds that 'E' is moving into, i.e. geometrical features.

3. Fig. 4.16 shows that only very faint velocity components are observed in the SE part of NGC 6888. This could be due to:
(a). Previous asymmetric ejection from the star along the equatorial axis, which is the major axis of the ellipsoid observed now. Later stellar winds interacting with this ejecta and the ISM could have displaced or condensed the ejecta such that there exists emitting material in the NW, but the same processes may not have occurred in the SE because of less dense ambient medium in the SE. This also suggests an inhomogeneous composition of the surrounding ISM, around NGC 6888.

(b). Proper motion of the star along the minor axis transverse to the line of sight may create a stellar wind 'bowshock', which could form an open parabolic arc (Van Buren and McCray 1988). From the CCD images, the star appears to be slightly offset from the center, by about 0.3-0.5 pc along the minor axis towards the NW, which suggests the preceding reason may be true.

IV.10. Scenario for the formation and evolution of NGC 6888

Johnson and Hogg (1965) first proposed that ring nebulae such as NGC 6888 are produced by strong stellar winds that sweep up the interstellar medium. These interactions may also involve stellar ejected material. In the following discussion a composite scenario consisting of the ejection of a shell or slow wind, followed by the subsequent 'sweep-up' or interaction of this ejecta and/or ambient medium with fast stellar wind is proposed. Winds are now recognized to be the important mechanism in the shaping of several types of shells or nebulae. In these 'interacting winds' models (Castor, Mc Cray and Weaver 1975, Balick 1987 a,b, etc), a 'fast wind' with high velocities (up to 2000 km s\(^{-1}\)) and mass loss rates of 10\(^{-7}\) to \(10^{-8}\) M\(_{\odot}\) yr\(^{-1}\) overtakes and drives a shock wave into a former red giant envelope or stellar ejecta (velocities of 10 km s\(^{-1}\) and mass loss rate of 10\(^{-4}\) to \(10^{-5}\) M\(_{\odot}\) yr\(^{-1}\)), creating a bright shell within the envelope. As the morphology and the physical parameters already derived for NGC 6888 resemble
known end results of these type of interactions, an interaction of a similar nature has also been assumed here.

I. Hα Shell

The ionized inner shell and especially the knots observed in NGC 6888 was found to be enriched in N and He, especially the 'knots' located in the shell, and this implies a stellar origin for the shell. This suggests that the ionized shell can be thought of as a slow mass (analogous to a RGE) ejected from the central star prior to the $2 \times 10^4$ yrs lifetime of the nebula. This is supported by the fact that the enriched mass is determined to be a significant fraction of the ionized shell mass.

This situation is similar to that in E-type nebulae that are enveloped by bubbles (Chu 1981). E-type nebulae as characterized by Chu, have clumpy appearances that are due to anisotropic ejection from the star or Rayleigh-Taylor instabilities. RCW 58 (Chu 1981) is an example of such a WR ejecta enveloped inside a bubble, which is thought to have ejecta that was produced before the turn-on of the WR wind. Similar N and He enriched knots are found in the Hα shell, interior to the wind-blown bubble in NGC 6888, suggesting stellar origins in this case too. The elliptical appearance of the shell suggests that the ejecta was ejected with nearly isotropic momentum flux and significant equatorial density enhancement. The bipolar nature of the X-ray observations also attests to equatorial ejecta enhancement. Possible methods by which there could be asymmetric ejection from the central star include:

(a). Stellar Rotation: Poe and Friend (1986) hypothesised that stellar rotation in young stars can cause the development of changes of wind density and velocity with polar angle.

(b). Inhomogeneous Medium: Expansion of the original ejecta into
inhomogeneous medium could be a possible explanation. NGC 6888 is located inside a multicomponent hierarchical gas-dust complex created by the Cyg. OB 1 association and its associated clusters NGC 6913 and IC 4996 (Lozinskaya and Sitnik 1987).

The mass in the ionized H$\alpha$ shell was determined to be $\sim 5$ M$_\odot$, which is low enough to make the stellar ejecta model viable. Assuming that the local ambient density is very high $\sim 10$ cm$^{-3}$, it was found that the wind-swept ISM could account for a significant fraction of the shell mass. For ejecta of initial mass $M_0$ and velocity $V_0$, the motion of the nebula, (which is constituted by ejecta and accreted ISM) can be described by equations describing mass accretion and momentum (Chu and Treffers 1981):

$$\frac{dM(t)}{dt} = n_0 A(t) V(t)$$

and,

$$M(t) V(t) = M(0) V(0) = M_0 V_0$$

where $M(t)$ is the total nebular mass as a function of time $t$, $n_0$ is the ambient density, $A(t)$ is the cross section of the nebula, and $V(t)$ is the translational velocity of the nebula. We note that in this case, as the nebula is assumed to have equatorial enhancements, the deceleration will not be as uniform as in the case of a spherically symmetric system.

The expanding ejecta and later the wind sweep up large amounts of ISM material, as the circumstellar shell expands outwards. The shell is partly ionized by the central WN star, and this is the observable ionized shell. The outer part which contains predominantly wind-swept ISM is thought to form the neutral outer shell. The mass of the ambient material being swept up by the stellar wind can account for the major part of the neutral shell mass $\sim 40$ M$_\odot$.

II. Fast Stellar Wind

The CCD imagery also showed an [O III] bubble that stretched beyond the H$\alpha$
ejecta shell in the NW, and [O III] lattice in the SE. No Hα or [N II] emission is observed in these bubbles. The [O III] bubbles thus appear to have originated by a different mechanism than the Hα shell. We suggest that the [O III] bubbles are actually parts of a wind-blown bubble created by fast winds, that is now enveloping the stellar ejecta. The [O III] line can become enhanced compared to Hα behind a shock (Shull and McKee 1979), which may explain the absence of Hα emission in this region. The corresponding Hα emission in the bubble may be below the detection limit, if the ambient gas density is low enough.

We now extend our proposed scenario to include this fast wind that eventually leads to the observed [O III] bubble. The 'slow wind' or ejecta referred to in the previous section, expands homologously till 'fast' (v ~ 1000 km s⁻¹) isotropic stellar wind overtakes it. This stellar wind has a mass loss rate of 2.5 x 10⁻⁴ M⊙ yr⁻¹ over a period of 2 x 10⁴ yrs. as observed. We note that this wind could also provide material enriched in N and He.

Kahn and West (1985) describe the subsequent evolution of the hot-bubble interior as it snowplows into the 'previous ejecta'. The snowplow pushes more quickly in the polar direction than along the equator, as there is less pressure opposing the stellar wind along the polar axis because of the equatorial density enhancement of the ejecta distribution. This type of interaction can cause an 'early elliptical' (Ballick 1987a) type nebula, as is the case here to eventually become prolate ellipsoid (Kahn and West), or if the density contrast between the polar and equatorial axis is larger, peanut or butterfly shaped.

The temperature in the hot, shocked stellar wind region i.e. in Castor et al 's (1975) region 'b' is given by Bochkarev & Lozinskaya (1983):
\[ T_b = 4.75 \times 10^6 \left( R_s n_0 v_{100}^3 \right)^{2/7} K \]

(4.27)

Where \( R_s \) is the shell radius in pc., \( n_0 \) is the ambient density, and \( v_{100} \) is the expansion velocity of the shell in units of 100 km s\(^{-1}\). Values of \( R_s = 3 \) pc., \( n_0 = 10 \) cm\(^{-3}\) as derived previously, and \( v_{100} = 0.85 \), gives a value of \( T_b = 1.1 \times 10^7 \) K. The average \([\text{N II}]\) \( T_e \) in the shell was previously determined to be \( \sim 9000 \) K, from the spectrophotometry of the knots. This gives

\[ T_{\text{wind}} = 10^3 T_{\text{ejecta}} \]

(4.28)

Assuming a conservation of pressure across the wind and the shell, gives:

\[ \text{Density}_{\text{wind}} = \text{Density}_{\text{ejecta}} / 10^3 \]

(4.29)

As the density of the hot stellar wind interior to the ejecta shell is low, the emission measure is also small enough to render it unobservable. During the lifetime of the nebula, the stellar wind cannot cool from the high temperature produced by the passage of the shock, therefore the hot stellar wind interior to the shell is not observable optically. X-ray observations of NGC 6888 corroborate the presence of this wind. The X-ray observed spectral distribution (Bochkarev 1988) agrees with that predicted for nebula formed by isothermal winds; where the temperature drop and rise in density from the center to the boundary of decelerated stellar wind results in an enhancement of the low-energy tail of the spectrum.

III. Evolution of the Bubble

From the CCD images, there is obvious interaction between the stellar wind and the ejecta/ISM ring. The hot, low density wind approaches the ejecta, and squashes some of the equatorially aligned ejecta towards the minor axis. This is what accounts for
the material found in the NW and W. Some of the material found in the NW and W is also wind-swept ISM.

These interactions also create Rayleigh-Taylor instabilities that were found to be the most likely mechanisms for the formation of the observed knots, from the comparison of the growing time of such instabilities to the time required to stop such knots expanding into the ambient ISM. The knots also suggested that the shell is now in a decelerating phase, i.e. the observed velocity is much less than the initial velocity.

IV. The Observed Bubble

The material along the NW-SE offers less pressure resistance to the hot wind, because of low density ejecta in this region as previously mentioned. When the slow wind or the Red Giant Envelope (RGE) is punctured, the hot gas in the interior bubble is no longer confined, and escapes through the boundary. This is visible as the [O III] bubbles in the NW, and the 'lattice' in the SE. The [O III] bubbles in the NW appear to be thin sheets of gas that are relatively free of instabilities. This also suggests that these bubbles are wind blown (Chu 1981). This situation appears to be similar to other formerly elliptical PN, where lobes of expanding gas have been observed to appear as bubbles along the minor axis during the occurrence of such a process (Balick 1987).

The density is much lower in these bubbles, on the order of 1-10 cm$^{-3}$ as discussed in a previous section, as they are not opposed by the ejecta pressure anymore. As the emission measure is proportional to $N_e^2$, these bubbles are faint in the optical and not visible in the X-Ray observations. In the SE the expanding gas is visible in a 'lattice' like structure. The faint emission in the SE may indicate low density ambient medium in that region, which allows the wind in the SE to dissipate faster, or fall below the observable emission measure. We have already discussed the possibility of
inhomogeneous ambient medium around the nebula. The 'lattice' or honeycomb appearance suggests instabilities created by the expansion of the fast wind into the inhomogeneous medium in this area.

The pressure interior to this bubble as well as ram pressure by the ambient ISM now constrains the inner ejecta/ISM shell from free expansion. In the absence of this pressure, the observed knots in the ionized shell would have fallen below the Palomar Sky Survey detection limit in $2.4 \times 10^3$ yrs, when their sizes would have tripled.

The bubbles in the NW are visible mainly in [O III]. Weak H I lines are observed in the NO3 position that corresponds to the bubble, but ions with lower ionization potentials such as [N II], [S II], He I etc. are not observed at all. This indicates a shock with incomplete recombination. The optical shell emission observed in the [O III] is produced in the incomplete cooling region behind the stellar wind shock wave. Therefore, the shock must have been preionized or back ionized, then the passage of the wind can ionize it further to [O III]. UV from the WN central star keeps it ionized, such that it cannot recombine back to [O II]. We note that these bubbles are similar to Cygnus Loop Type II features (Hester, Parker, Dufour 1983), which are thought to be located in the hot end of the recombination region, and are due to nonsteady flow.

The evolution and the motion of the bubble and ejecta ring follow a complicated path. The values of $\varepsilon$ and $\pi$ calculated assuming the nebula consists of ionized as well as neutral mass ($\sim 40 \ M_\odot$) indicate that the nebula is in the energy conserving phase. For a scenario such as this where the stellar winds provide substantial kinetic energy flux in addition to the stellar radiative flux, the static case described by a standard Stromgren sphere analysis is not appropriate, although the overall emission in the shell is found to be characteristic of photoionization processes. The dynamics of this type of interaction is described by Weaver et al. (1977), Castor et al. (1975), Johnson
and Hogg (1965), etc, based on simple conservation arguments. In reality, the measured energetics of the bubble consists of contributions from the ejecta that is mixed into the bubble as well, and therefore this is not a classical 'wind-blown' bubble situation. As the initial energy and momentum of the ejecta shell is unknown, it is not possible to correctly determine if the bubble is in an energy or momentum conserving phase. For the same reason, equations describing the dynamics of classical wind-blown bubbles are relevant but not completely valid in this case. This also explains why the observed X-ray flux is less than the theoretical flux estimate.
Figure 4.5. BPT (1981) plot showing the relationship between the $(\lambda 6584/\lambda 6563)$ and the $(\lambda 3727/\lambda 5007)$ intensity ratios. Symbols: Normal H II regions - $\bigcirc$, Detached Extragalactic H II regions - $\Delta$, Planetary Nebulae - $+$, NGC 6888 original points - $\square$, NGC 6888 corrected points - $\equiv$. Arrows point towards direction of correction.
Figure 4.6. BPT (1981) plot showing the relationship between the $(\lambda_{5007}/\lambda_{4861})$ and the $(\lambda_{6584}/\lambda_{6563})$ intensity ratios. Symbols: Normal H II regions - O, Detached Extragalactic H II regions - A, Planetary Nebulae - +, NGC 6888 original points - □, NGC 6888 corrected points - □. Arrows point towards direction of correction.
Figure 4.7. Binette (1985) plot showing [O III] / Hβ vs. [O II]/[O III] for Binette models - symbols are cross referenced. NGC 6888 positions - ♦. Fiducial marks represent successive values of Log(U). The power law index is shown to the left of the curves.
Figure 4.8. Figure showing the ionization term $\text{[3727]/[5007]}$ as a function of distance from the WR star, for NGC 6888 positions.
Figure 4.9. IRAS LRS Spectrum of NGC 6888 (Van Buren & Mc Cray 1988). The two broad features are the 9.0 μm line of Ar III and the 15.5 μm line of Ne III. These are typical lines found in high-excitation planetary nebulae. The broadening is caused by the extent of the source.
Figure 4.10.a. IRAS 100 μm image of NGC 6888.

Figure 4.10.b,c.CCD [O III] and [N II] images boxcar smoothed with a box of 100,100.
Figure 4.11. [O III] Emissivities as a function of $T_e$. 

Emiss. (5007,52,88,121) vs $T_e$
Figure 4.12.a. Histogram of a section including Hα knot + diffuse emission only.

Figure 4.12.b. Histogram of a section including [O III] bubble section only.
Figure 4.13. Spectral response vs. wavelength of optical components. Solid lines show the transmission of filters and lenses.
Figure 4.14. Measurement of linear dimensions of 'knots', by fitting Gaussians to 1-D slices.
Figure 4.15. Isophotes of soft X-ray emission from NGC 6888, superposed onto the optical image of the ring nebula.
Figure 4.16. Spectrophotometric positions from this study superposed onto the Hα velocity spectral map (Treffers and Chu 1982). The spectra are located on a grid with spacings of 2′.
V. CONCLUSIONS

In Chapters III and IV we analysed our observational results to probe the morphology, ionization structure, composition and formation mechanism of NGC 6888. In this chapter all the results discussed in previous chapters are summarized, to get an overall picture of NGC 6888. We conclude with suggestions for future studies concerning this and related topics.

V.1. SUMMARY OF RESULTS CHARACTERIZING NGC 6888

V.1.a. Diagnostics

From the distinct morphology of the nebula in [O III] compared to Hα and [N II], coupled with the high [O III] $T_e$ in comparison with the [N II] $T_e$, we can parametrize the structure of NGC 6888 as consisting of two basic physical systems:

(i). The 'Hα' + [N II] shell and knots

Emission exists in this zone in all the emission lines - Hα, Hβ, [N II], [O III] and [S II]. This zone encompasses the diffuse emission inside the ellipsoid and also the interspersed knots that are rich in [N II] and Hα. The physical parameters prevailing here, as determined from the spectrophotometry of about 8 knots in the NE, NW, W and SW are on average:

[N II] $T_e = 9000$°K [O III] $T_e = 14,000$°K [S II] $N_e = 400$ cm$^{-3}$

(ii). The '[O III]' Bubble

Features seen only in [O III] are found in this zone. This zone includes the bright [O III] rim enclosing all the ellipsoidal region which is the Hα shell, and bubbles in the NW and lattice in the SE that extend beyond the ellipsoid boundaries, in these
regions. The [O III] $T_e$ characteristic to this zone is:

$$[O 	ext{ III}] T_e = 50,000 \, ^\circ\text{K}$$

It was not possible to determine an [S II] $N_e$ or a [N II] $T_e$ for this zone, as this zone does not have any of the 'cooler' (lower ionization potential) ions including [S II] and [N II]. But we note that this zone, especially the bubble has a lower emission measure than the ellipsoid, which suggests a lower density in the bubble.

V.2. Mass of the Nebula

The nebula consists of an ionized part and a neutral part, where:

(i). Ionized Mass

The ionized mass of the nebula was determined from the H$\alpha$ luminosity determined from the H$\alpha$ surface brightness image ($\sim 3.2 \times 10^{-9}$ ergs cm$^{-2}$ sec$^{-1}$), and the emitting volume. The ionized mass was determined to be $5 \, M_\odot$. This is the mass of the observed optical emission of the H$\alpha$ shell. The value of the filling factor used for the mass estimate was $f = 0.008$, derived using average values ($N_p$, etc.) from the observed knots. This value of the filling factor is very low compared to the average for PN ~ 0.05. This implies that the nebula is a large, extended, clumpy nebula. An average value of $N_e = 400 \, \text{cm}^{-3}$ determined from the [S II] in the spectra of the knots was assumed for the derivation of the filling factor.

(ii). Neutral Component:

The neutral mass of the nebula was calculated by extrapolating to the IR, specifically the fluxes of the [O III] 52$\mu$m and 88 $\mu$m from the observed [O III]$\lambda 5007$ emission. On comparing with observed IRAS fluxes at these bands, these contributions were found to be insignificant ($< 30\%$). This confirmed that the majority of the observed IR emission originates in neutral material in the nebula. This method resulted in a large
neutral mass estimate ≈ 40 $M_\odot$ that agreed with the mass estimated by Marsden and Meaburn (1988) from IRAS data directly. No neutral lines such as [O I] $\lambda$6300 were found in (except one) the observed spectral positions. Also the neutral mass is significantly larger than the ionized mass. This suggests that the neutral mass is not mixed with the ionized mass, but is actually a shell around it.

**V.3. Mass Components**

To study the components that go into creating the mass (neutral and ionized), that is observed ≈ 45 $M_\odot$, the contribution from the following were investigated:

(i). **Enrichment or Ejecta Mass:**

Overabundances observed in the total elemental abundances of N and He suggested that the observed shell was enriched with processed material from the star, as WN stars are found to be rich in helium and nitrogen as a result of evolution. On calculating the fraction of N/He contributed to the shell from the same ratio in the stellar spectra, the enriched mass was found to be about 3-6 $M_\odot$. This is a significant fraction of the ionized shell mass (≈ 5-10 $M_\odot$), which suggests that there is ejected material from the star present in the ionized shell.

On the other hand, the enrichment mass is much less than the total mass (ionized + neutral) of the nebula. If this nebula is representative of similar WR shell nebula, this suggests that mass loss from WR stars does not contribute significantly to the enrichment in nitrogen and helium of the interstellar medium; more significant contributors being planetary nebula and supernovae at least for nitrogen (Peimbert 1978).

(ii). **Wind-loss Mass:**

The mass lost over the dynamical lifetime (2x $10^4$ yr) of the star using a mass
loss rate $dM/dt = 2 \times 10^{-5} \, M_\odot/\text{yr}$, was found to be only about $0.5 \, M_\odot$, also an insignificant part of the ionized, and of course, total mass.

(c). Wind-Swept ISM mass:

The above results suggest that the majority of the mass existing in the nebula is actually ISM mass that was 'swept up' by a material flowing out of the WN star, as suggested by Johnson and Hogg (1965). Conservation equations (Van Buren 1986), for the dynamics of a swept-up shell expanding with a velocity $v_e$ into an ambient medium of density $\rho_0$, assuming pressure balance, gives a high value for the ambient density $\sim 8 \, \text{cm}^{-3}$ around NGC 6888.

This is not surprising, as the nebula is located interior to the Cygnus OB 1 association. Also IRAS data indicates the presence of molecular clouds in this region (Marsden and Meaburn 988). This high value of $\rho_0$ leads to a swept-up ISM mass of $\sim 20-60 \, M_\odot$. This calculation shows that there is a good agreement between the remainder of the shell (neutral + ionized) mass and that calculated for the swept up ISM mass, which implies that a large percentage of the shell mass could be swept up ambient mass.

V.4. Energy vs. Momentum Conservation

The assumption of neutral mass existing in the nebula leads to larger estimates of mass $\sim 45 \, M_\odot$ in NGC 6888. This points to NGC 6888 being in the energy conserving phase, as the energy efficiency parameter $\varepsilon = 0.18$ and momentum efficiency $\pi = 5.6$.

We note though that the NGC 6888 [O III] bubble is not a classical wind-blown bubble, as there is ejecta material from the shell mixed in. The currently measured kinetic energy and momentum includes the shell contribution that cannot be
estimated as the initial energy and momentum are unknown. For this reason, we cannot really define the state of the bubble.

V.5. Radio Observation

The radio emission corresponds spatially with the optical emission of the Hα + [N II] zone. There was no evidence of non-thermal emission in the radio observations.

V.6. X-Ray Observations

X-ray observations recorded bipolar sources along the major axis of the nebula, i.e. centered on NE and SW. This corroborates our idea that the nebula was originally ejected in a bipolar way, i.e. the ejecta is denser along the equatorial plane. X-ray emission found interior to the shell suggests that the shell has hot, shocked gas inside.

The observed X-ray luminosity is found to be less than that predicted form bubble models, as the presence of ejecta in the bubble complicates the energetics.

V.7. Velocity Measurements

Radial velocity measurements suggest that the Hα+ [N II] zone in the nebula is an ellipsoidal shell, with the NE side inclined towards the observer at an angle of 20° -40° to the plane of the sky. A fit to the radial velocities gives a velocity ellipse that indicates a bubble expanding at about 85 km s⁻¹ with a radius of ~ 2.95 pc. The observed projection of this appears to be elliptical with the major axis measuring about 7.8 pc., and the minor axis measuring 3.9 pc.

The above model was used to correct for projected distances of observed knots. Ionization as determined from the [O II] λ3727+3729 / [ O III] λ5007 ratio was found to be an inverse function of the square of the true distances of the knots, as was
suspected from the line ratio variations for ratios such as [N II] $\lambda 6584$ / $H\alpha$ and [O III] $\lambda 5007$ / $H\beta$. This shows that ionization falls off as a function of distance from the WR star, in accordance with the results indicated by photoionization models.

**V.8. Photoionization Model**

Two of the observed positions NE2-W and NW1-W were fit using Shield's (1978) photoionization code 'nebul', using a $T_{\text{eff}} = 55,000$ °K for the star. The good fits that were achieved by the model indicates that the overall emission in the nebula is dominated by photoionization processes due to the central star. The model results suggested that O/H is depleted in the nebula by about 0.9 dex compared to galactic H II regions, and N/H is enriched by about 0.6 dex. He/H was also found to be enriched by 0.15-0.30 dex in comparison to galactic H II regions. The unusual O/H depletion is unexplainable at this point, although this situation could be similar to other N enriched and O depleted shell nebulae like η Car, and NGC 6164-5. The model used may have decreased the resultant intensities of the O emission lines, as decreasing O in the input abundance may result in the cooling shifting to other lines such as N.

The model also demonstrated that a significant change in the 'ionization parameter U' alone was sufficient to bring about the correct ionization level change from one position to another, as well as fit the individual emission line strengths (for [O II] $\lambda 3727, 29$, [O III] $\lambda 5007$ and [N II] $\lambda 6583$, in particular), to a close approximation. As an example, to go from an [O II]/[O III] = 1.2 in the NW to an ionization ratio = 0.18 in the NW, the ionization parameter U had to be changed by an order of magnitude. ($U = 2.3 \times 10^{-4}$ in the NE and $U = 2 \times 10^{-3}$ in the NW). This demonstrated that ionization was the primary reason for variations in line intensities from one region to another.
V.9. Knots - Origin and Evolution

The knots are measured to be of uniform length ~ 6.5" = 0.046 pc. The time required for the ram pressure of the ambient medium to bring the knots to rest is about 2 x 10^4 yrs. This is also similar to the lifetime of the nebula, which indicates that the nebula is in a decelerating phase. This implies that the observed velocity is less than the initial expansion velocity, which in turn suggests that the dynamical age of the nebula may be less than that estimated.

The growing time of Rayleigh-Taylor instabilities (~1.3 x 10^3 yrs.) is determined to be significantly less than the stopping time ~ 2 x 10^4 yrs. This indicates that Rayleigh Taylor instabilities are the most plausible mechanisms for the formation of the knots.

The dissipation time for the knots to fall below the Palomar Sky Survey detection limit was estimated to be 2 x 10^3 yrs. This indicates that the knots are actually interior to the bubble and ambient ISM, which exerts pressure on them to maintain them in their observed sizes.

From the salient characteristics determined for NGC 6888, as discussed in the preceding section, a plausible scenario was constructed that explains the formation and the current status of NGC 6888. The main features of the proposed scenario are:

V.10. **PROPOSED SCENARIO:**

1. The ionized inner Hα shell is assumed to be a slow wind originally ejected from the star in an asymmetric manner. This shell is constituted by stellar ejecta, as attested to by the N and He enriched knots, and swept-up ambient ISM.

2. The other distinct morphological component is the [O III] bubble in the NW and lattice in the SE. No Hα or [N II] is observed in this bubble. This is proposed to be
parts of a wind-blown bubble that is now enveloping the stellar ejecta.

3. It is proposed that a 'fast wind' ultimately leads to the [O III] bubble. This fast wind interacts with the pre-existing slow wind. This snowplow exerts more pressure along the polar axis, as the ejecta (slow wind) was proposed to be equatorially enhanced. The interaction of the fast wind with the slow wind and ambient ISM creates instabilities. Rayleigh Taylor instabilities were found to be the most plausible mechanisms for the knots found in the Hα shell.

4. The fast wind punctures the low density ejecta in the polar axis, and escapes as bubbles. As the bubbles/lattice is only observable in [O III], a shock with incomplete recombination is indicated. This suggests that the shock was preionized, and UV photons from the WR star maintains the ionization.

5. Theories of classical wind-blown bubbles are relevant but do not correctly apply to the evolution and energetics of the bubble in the case of NGC 6888 as ejecta material is mixed in with the wind-blown bubble.

V.11. Proposals for Future Research

NGC 6888 is found to consist of several physical features that vary on a very small scale. As a result, prevailing conditions such as $T_e$, $N_e$ and pressure are also different. A more detailed velocity and spectrophotometric study is required. This would enable one to fit more detailed dynamic models of wind-blown bubbles and shells to separate the two components more distinctly. A detailed velocity map, especially of the [O III] bubble would help correlate the geometry to proposed physical processes. A more detailed spectrophotometric study, in particular of positions corresponding to the
bubble as well as the diffuse material interior to the shell would enable one to fit photoionization and shock ionization models to distinct parts of the nebula. This would help identify where in the nebula these competing processes are more important.

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REFERENCES


