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FILAMENTARY STRUCTURE

IN

PLANETARY NEBULAE

DISSERTATION

Presented in Partial Fulfillment of the Requirements for
the Degree Doctor of Philosophy in the Graduate
School of The Ohio State University

By

Gregory O. Boeshaar, B.S.

* * * * *

The Ohio State University
1972

Approved by

A handwritten signature in dark ink, appearing to read "Stanley J. Gyzak", is written over a horizontal line.

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Chapter 1

INTRODUCTION

General Considerations

Several major reasons exist for the astrophysical attention given planetary nebulae. At some point in many a star's life cycle between its existence as a red giant and its lingering white dwarf death, mass is expelled into the interstellar medium. The glowing gas of the planetary marks its central star's passage through this phase. In addition, planetary nebulae afford observers a detailed view of an expanding ionized gas cloud surrounding a hot central radiation source. Such a phenomenon may have application to objects too distant for their own structure to be resolved, such as the nuclei of Seyfert galaxies. The brief summary of the general properties of planetaries that follows is drawn from reviews on the subject by Aller (1956), Seaton (1960), Osterbrock (1964), Aller and Liller (1968), Osterbrock and O'Dell (1968), and Aller (1969).

1036 galactic planetary nebulae have been catalogued by Perek and Kohoutek (1967), from which the total number in the Galaxy is estimated to be on the order of 10,000. Distances to these objects remain uncertain due to difficulties in the application of the available yardsticks, i.e. statistical parallax, the

comparison of the expansion radial velocity with corresponding tangential motions, or the combination of the measured H β line flux with determinations of the electron density, angular size, plus the percentage of the nebular volume containing emitting matter (the filling factor). An extensive catalogue of distances for planetaries has been published by Cahn and Kaler (1971), who calculate a galactic birthrate of 42 per year for these predominantly disk population objects (the most notable exception being the extreme population II planetary in the globular cluster M 15).

Optically, the spectrum of a typical planetary nebula consists of bright lines overlying a relatively weak continuum. The emission lines arise primarily from three mechanisms. The permitted lines of H 0 , He 0 , and He $^+$ result from photoionization by stellar ultraviolet photons followed by the capture of free electrons and their subsequent cascade to the ground state. Emission lines due to forbidden transitions, i.e. those not permitted by electric dipole selection rules, are observed for various atoms and ions heavier than helium. These lines are due to the collisional excitation by free electrons of low lying terms in the ground state configurations of these atoms and ions. The third major process, a sequence of chance coincidences, produces the Bowen fluorescent lines in high excitation nebulae. The He II Ly- α photon at λ 303.8 has an energy equal to an excitation energy of O $^{+2}$, and overpopulates this upper level. The following cascade to the ground state produces enhanced permitted lines for this ion. One of these lines at λ 374.4 matches an excitation energy of N $^{+2}$, producing

enhanced permitted lines for this ion, too. A fourth mechanism gives rise to weak permitted lines of oxygen, carbon and other ions in some nebulae. This mechanism involves the direct excitation of ions by the absorption of stellar continuum radiation, as proposed by Seaton (1968).

Like the emission line spectrum, the nebular continuum originates from three basic processes: free-bound electron transitions from the continuum to the excited states of hydrogen and helium, free-free transitions of electrons accelerated by ions (responsible for the thermal radio emission detected from some planetaries), and 2-photon emission in hydrogen via a transition from the 2s to the 1s level. This latter transition, forbidden by the $\Delta l = \pm 1$ electric dipole selection rule, occurs indirectly, proceeding through an intermediate "virtual" level. This produces two photons, the sum of whose energies equals the excitation potential of the 2s level.

Many planetaries showing continuous infrared radiation in excess of predicted intensities have been observed (Gillett, Low, and Stein 1967, Woolf 1969, Gillett and Stein 1970, Gillett, Knacke, and Stein 1971, Gillett, Merrill, and Stein 1972). In some cases, this excess represents a sizeable fraction of the entire energy output of the nebula. While it has been suggested that this is the result of unresolved line emission (Goldberg 1968), Gillett, Merrill, and Stein (1972), on the basis of observations of over thirty planetaries, have concluded that the infrared excess is composed of true continuum as well as line emission. Krishna Swamy and O'Dell (1968) and Krishna

Swamy (1969) have attributed this excess radiation to thermal re-emission by dust particles of trapped Ly- α radiation.

In both the optical and radio frequency ranges, the relative fluxes of certain emission lines, the absolute H β line flux, plus some continuum observations can be used in various combinations to determine the relative chemical abundances, the electron density, and the electron temperature of the nebular gas. The electron temperature is defined in terms of the mean velocity, v_e , for a Maxwellian distribution of free electron velocities in the nebula via

$$\frac{1}{2} m_e v_e^2 = \frac{3}{2} k T_e. \quad (1)$$

Studies of emission line profiles yield average expansion velocities of 20 to 25 km/sec, which, along with estimated maximum radii of 0.7 pc., indicate lifetimes on the order of 10^4 to 10^5 years for planetaries.

Structurally, planetary nebulae exhibit a large scale stratification consisting of concentric Strömgren spheres (Strömgren 1939) for various ions. These are layered according to their ionization potentials, with the highest ionization states lying closest to the central star. Theoretical models in general agreement with the above description have been constructed (Goodson 1967, Flower 1968, 1969, Harrington 1968, 1969, Williams 1968, Kirkpatrick 1970, Buerger 1971) using the relations for thermal balance in a gas heated via photoionization by a diffuse stellar radiation field and cooled through nebular line and continuum emission. These radiation fields arise

from central stars that have surface temperatures estimated to be in the range of $30,000^{\circ}\text{K}$ to greater than $100,000^{\circ}\text{K}$. Review material on the central stars of planetary nebulae and their evolution has been presented by Heap (1970) and Salpeter (1971).

Small Scale Nebular Structure

The preceding simplified description does not take into account small scale inhomogeneities in planetary nebulae. Photographic evidence for detailed structuring in many planetaries has been presented by Minkowski (1968) and Capriotti, Cromwell, and Williams (1971). For many other planetaries too far away to have small scale features individually resolved, cursory inspections of the photographs and sketches by Curtis (1918) show irregularities in surface brightness plus departures from expected circular or elliptical symmetry. The most striking example of such structure is NGC 7293, the Helix Nebula in Aquarius, shown at various scales in photographs by Baade (referred to by Menzel 1950, Zanstra 1955, and Capriotti 1972a), Carranza, Courtès, and Louise (1968), Vorontsov-Velyaminov (1968), and Araya, Blanco, and Smith (1972). Many bright condensations with filaments extending radially away from the direction to the central star can be seen to have the approximate dimensions of $1''$ by $30''$ of arc (Vorontsov-Velyaminov 1968). Since these condensations are separated by about $4''$ to $5''$ of arc, such structure would not be resolvable in any other planetary nebulae, because NGC 7293 has the largest angular diameter of any of these objects by

at least a factor of four (Capriotti 1972a). For more distant nebulae, unresolved filamentary clumps would manifest themselves as irregularities in surface brightness, such as those mentioned previously.

Other anomalies exist in viewing planetaries as homogeneous objects. Nebulae such as NGC 2440 and NGC 7027 show extreme ranges of excitation coexisting, with emission lines of [Mg I] to those of [Ne V] and O IV in the same localized area (Aller, Czyzak, and Kaler 1968). For NGC 7027, Seaton and Osterbrock (1957) found an electron density of 3000 cm^{-3} or 8500 cm^{-3} depending on which criterion they used (e.g. either the ratio of the [O II] lines $\lambda 3726$ to $\lambda 3729$ or $\lambda \lambda 3726, 3729$ to $\lambda \lambda 7320, 7330$). This discrepancy being too large to be due to either observational error or errors in atomic parameters, they attributed the difference to true density fluctuations of this magnitude within the nebula. Other investigators (Kaler 1966, Weedman 1968, Saraph and Seaton 1970) have found the value measured for the electron density of a given planetary to vary from one criterion to another.

Inconsistencies seem to be evident in measured electron temperatures. Kaler (1970) noted that temperature values derived from hydrogen radiations, using either the strengths of the radio recombination lines and underlying free-free continuum or the ratio of the Balmer continuum to the H β flux, are about half the values obtained from observations of the [O III] lines. Goldberg (1966) suggested that the anomalies in the temperature based on hydrogen recombination lines might result from a substantial fraction of the

line energy being due to stimulated emission. This, he argued, would arise from an overpopulation of high hydrogen levels brought about by deviations from thermodynamic equilibrium in the nebulae. But hydrogen temperatures derived from measurements of the Balmer continuum and the H β flux are also low with respect to the [O III] temperatures. This led Peimbert (1967) to suggest that the temperature variations are real, with the hydrogen emission and the [O III] emission coming, respectively, from low and high temperature subregions of the nebulae. Such temperature fluctuations along the line of sight, if not taken into account, can cause significant errors in the determined relative abundances of oxygen, nitrogen, and neon, according to Rubin (1969).

Homogeneous models constructed for relatively symmetric planetaries do not provide complete agreement with observations. Harrington (1969) pointed out the difficulty in explaining the wide ionization range observed on the basis of homogeneous models. He also discussed a problem encountered by other investigators (Williams 1968, Flower 1969, Harrington 1969, Kirkpatrick 1970, Buerger 1971) for the lines of [S II], [N II], [O II], and [O I]: the emission line fluxes predicted by homogeneous models for these low ionization states are consistently below their observed strengths in the planetaries to which the models are applied. Another problem exists in that homogeneous models predict complete separation of the strata occupied by O^{+2} and N^{+} . However, observations by Wilson and Aller (1951) and by Osterbrock (1970) show a definite overlap in the regions of [O III] and [N II] emission which Osterbrock attributes

either to departures from spherical symmetry or to density fluctuations in the nebula.

Much effort has been made to resolve the difficulties discussed above. Khromov (1965) attempted to explain strengths of the [O I] $\lambda 6300$ line by maintaining that it originates in the H^+ to H^0 transition zone in optically thick, radiation bounded nebulae. O^0 and H^0 have nearly equal ionization potentials of 13.614 eV and 13.595 eV, respectively (Allen 1963). Khromov assumed the fractional abundances O^+/O^0 and H^+/H^0 to be equal. However the detailed calculations of Goodson (1967) and of Harrington (1968) indicate that this overestimates the O^0 abundance by more than an order of magnitude. Williams (1970) stated that this makes it unlikely that enough [O I] radiation is produced in the H^+ to H^0 transition region to explain the observations. Campbell (1968), using scanning spectrographic observations of eighteen planetaries, found that a direct correlation exists between the strengths of the [O I] $\lambda 6300$ line and the [N II] $\lambda 6584$ line. Also, the [O I] emission was an order of magnitude brighter than his calculations indicated. Campbell suggested that strong [O I] emission signifies that a nebula is radiation bounded, in line with Khromov's interpretation. Again, Williams' objection appears to be applicable.

Williams (1970) presented optically thin, high density condensations as the source of the high [O I] $\lambda 6300$ emission. These knots would also explain the difficulty with the small calculated [O II] $\lambda 3727$ and [N II] $\lambda 6584$ line strengths. A problem arises in that these condensations are not in pressure equilibrium with the

surrounding gas; consequently, they would have lifetimes of about 100 years. This is relatively short compared to planetary lifetimes, as Williams pointed out, and would require a constant regeneration mechanism. Dyson (1968), however, showed that cool ($T_e \approx 100^\circ\text{K}$) isothermal, optically thick knots would survive destruction by the stellar radiation field for the necessary 10^4 years nebular lifetime, if they had an initial radius of 10^{15} cm (compared to the quoted maximum nebular radius of approximately $0.7 \text{ pc} \approx 2 \times 10^{18} \text{ cm}$).

Capriotti, Cromwell, and Williams (1971) presented a series of filter photographs of NGC 6720 and NGC 6853 that show the [O I] $\lambda 6300$ and the [N II] $\lambda\lambda 6548, 6584$ emission coming mainly from small scale knots and filaments. They concluded that such emission arises from the ionized "skin" layers of optically thick, high density regions with neutral cores, having a "skin" density on the order of 100 times the ambient gas density.

Van Blerkom and Arny (1972) point out that the presence of optically thick condensations in planetaries would explain the bright knots with their radially trailing filaments observed in NGC 7293 in the following manner. The gas in the column behind the condensation would be shadowed by the knot from the stellar ionizing radiation. The ionization conditions in the shadow would then be determined by the diffuse nebular radiation with its characteristic effective temperature of about 10^4 K, leading to the predominance of singly ionized atoms. The surrounding unshadowed gas would be ionized by the stellar radiation field with characteristic effective temperatures that can exceed 10^5 K. Thus a real difference would exist

in the ionization states present in the two regions. When seen in the light of lines from singly ionized atoms, the shadowed gas would appear as a luminous filament with a bright "head" on the starward end. Furthermore, Harrington (1969) and Buerger (1971) have found that the inclusion of small scale inhomogeneities in the outer nebular shell can bring model calculated line strengths for singly ionized atoms into agreement with observations without destroying the previously attained agreement for lines from higher ionization states. Kirkpatrick (1970) found for NGC 7009 that a shell of optically thin knots did not correct these discrepancies.

Attempts to explain the formation of condensations via thermal instability (Zanstra 1955, Field 1965) have been shown ineffective (Daub 1963, Sofia 1966, Harrington 1968, Mathis 1968). Capriotti (1971) demonstrated that gravitational instability and "mock" gravitational instability with its Ly- α radiation shadowing by dust particles are unlikely mechanisms for the production of condensations. Magnetic fields have been shown not to contribute to planetary structure (Menzel 1968, Munch 1968). Vorontsov-Velyaminov (1968) attributes filaments to corpuscular streams ejected by the central star, but predicts expansion velocities much higher than those observed and cannot explain the luminous "head" on the end of the filament facing the star.

Capriotti (1972a) has proposed the following formation process for knots and filaments in planetary nebulae. In a young planetary, a neutral hydrogen shell surrounds the H^+ region. This H^0 shell undergoes an outward acceleration via thermal and dynamical

pressure on the ionization front; as it loses mass to the H^+ zone through ionizations at this front. A point is reached in the nebular expansion where the recombination rate becomes too low to suppress displacements of ionized gas across the ionization front away from the central star. At the same time, the ionization rate becomes too low to damp incursions of neutral gas across the front toward the star. Thus, an instability of the front develops similar to a Rayleigh-Taylor instability. This condition occurs at the interface of two incompressible fluids of different densities experiencing an acceleration. The H^0 spikes that now protrude into the H^+ zone are subjected to a shearing force as the result of a velocity difference between the two gases. The subsequent distortion and fragmentation of the neutral spikes leads to the formation of cold dense globules. After fragmentation the ionized gas flows past the optically dense condensations and the filamentary structure forms as a result of the shadowing phenomenon proposed by Van Blerkom and Arny. Capriotti calculates that, although the knots are eroded by stellar ionizing radiation, the central star's production of ionizing quanta will decrease rapidly enough at this stage of its evolution for the globules ultimately to retain 30 per cent of their initial mass (approximately 2×10^{27} gm). The "skin" of matter being ionized off the condensation provides the bright "head" observed for the filaments, such as those seen in NGC 7293. The filaments portrayed by Capriotti contain neutral and singly ionized atoms. They produce all of the [O I] nebular radiation. In addition, the excess (over model predictions) [O II], [N II], and [S II] radiation is provided by these features.

Statement of the Problem

Minkowski (1968) set the theme of this investigation in the following summarizing remarks to the 1967 IAU Symposium on Planetary Nebulae:

. . . I believe that one of our most urgent problems is that of trying to assess the consequences of picturing a planetary nebula as an envelope or shell with constant density, constant ionization, and constant electron temperature . . . we should try to estimate at least the order of magnitude of the errors that are now being committed by total disregard of the properties of real planetaries.

The problem concerns the observer. The photo-electric observations which are our most reliable source of information on the flux densities in the emission lines, and many photographic determinations, give us values integrated over the whole nebula. But, if we are to be able to assess the effect of filaments and condensations on the analysis of the results, we must know the conditions in these features.

. . . Differential observations of condensations and their surroundings are necessary to ascertain the conditions in condensations.

The purpose of this research is the observational determinations of the properties of the filaments and their surroundings, particularly with respect to the filamentary characteristics proposed by Capriotti (1972a) and by Van Blerkom and Arny (1972). Qualitatively, these results are compared with the integrated observational data available for the nebulae studied. The anomalies cited in the previous paragraphs are then discussed in terms of filamentary structure.

Chapter 2

APPROACH TO PROBLEM

Observational Procedure

In this investigation, the filamentary structure in planetary nebulae is studied by means of photographic spectrophotometry. Photoelectric methods were deemed unsuitable for various reasons. First, photoelectric observations give flux values integrated over large nebular regions (usually over the entire nebula), inseparably blending the contributions of filaments and surrounding gas. Second, they are useful only for strong to intermediate strength lines. The lines of primary interest here are often too weak to be accurately observed by this method. Finally, the photoelectric wavelength resolution is not sufficient to usefully separate such necessary emission lines as the [N II] $\lambda 6548$ line and H α at $\lambda 6563$, the [O I] $\lambda 6300$ line and the [S III] $\lambda 6310$ line, or the [S II] lines at $\lambda 6717$ and $\lambda 6731$.

The photographic spectra necessary for the study of small scale structure in planetaries were obtained in the following manner. Untrailed nebular spectra were taken by means of offset guiding on nearby stars. The slit of the spectrograph was held fixed on a specific section of the nebula a known angular distance from the

Fig. 1 - Average Nebular Appearance with Side View. The cross marks the position of the central star, the dashed line indicates the inner, high ionization portion of the planetary, and θ indicates the direction in which angular distance is measured across the nebula. The I and the II represent sample settings for the spectrographic slit, while A and B indicate lines of sight through the nebula.

central star or other reference point. A variation in the emission from an ionic species across the nebular region covered by the slit then appeared as an intensity variation along the emission lines (at right angles to the dispersion) of that ion on the spectrogram. Knowing the measured offset and the scale of the slit on the sky, structure along an emission line was related to specific features on direct photographs of the object under study. In addition, graded spectrograms were taken, with several exposures of different duration being made for each nebular area. This provided useful exposures for all lines since a wide range of intrinsic strengths exists among the various emission lines located in the spectral region under consideration.

Spectra were taken of the outer regions of planetaries exhibiting marked irregularities of surface brightness on photographs. At the distances of these objects, individual filaments are not observable. What one observes are packets of filaments appearing as surface brightness inhomogeneities. Figure 1 presents an idealized representation of this situation. Generally, planetaries show a highly ionized interior surrounded by a ring of irregular filamentary clumps. This ringlike configuration is the result of a projection effect as shown by the side view in Figure 1. The line of sight A intersects the radial filaments perpendicularly. For this reason, the nebular rim presents to the observer the maximum emitting surface area available per filament. A line of sight such as B that passes through the inner portions of the nebula is nearly parallel to the filaments. Because of the small apparent cross

Table 1
OBSERVED EMISSION LINES^a

ION	IONIZATION POTENTIAL (eV)	$\lambda(\text{\AA})$ OF OBSERVED EMISSION LINE	TRANSITION LEVELS	EXCITATION POTENTIAL OF UPPER LEVEL (eV)
H I	13.6	4861	$4^2\text{D} - 2^2\text{P}^{\circ}$	12.69
		6563	$3^2\text{D} - 2^2\text{P}^{\circ}$	12.04
He I	24.6	4713	$4^3\text{S} - 2^3\text{P}^{\circ}$	23.49
		4922	$4^1\text{D} - 2^1\text{P}^{\circ}$	23.63
		5016	$3^1\text{P}^{\circ} - 2^1\text{S}$	22.99
		5048	$4^1\text{S} - 2^1\text{P}^{\circ}$	23.57
		5876	$3^3\text{D} - 2^3\text{P}^{\circ}$	22.97
		6678	$3^1\text{D} - 2^1\text{P}^{\circ}$	22.97
		7065	$3^2\text{S} - 2^3\text{P}^{\circ}$	22.62
		7281	$3^1\text{S} - 2^1\text{P}^{\circ}$	22.82
He II	54.4	4686	$4^2\text{F}^{\circ} - 3^2\text{D}$	50.80
		5412	$7^2\text{G} - 4^2\text{F}^{\circ}$	53.08
		5914	$26^2\text{H}^{\circ} - 5^2\text{G}$	54.11
		5932	$25^2\text{H}^{\circ} - 5^2\text{G}$	54.10
		5953	$24^2\text{H}^{\circ} - 5^2\text{G}$	54.09
		5977	$23^2\text{H}^{\circ} - 5^2\text{G}$	54.09
		6005	$22^2\text{H}^{\circ} - 5^2\text{G}$	54.08
		6234	$17^2\text{H}^{\circ} - 5^2\text{G}$	54.00

Table 1 (continued)

ION	IONIZATION POTENTIAL (eV)	$\lambda(\text{\AA})$ OF OBSERVED EMISSION LINE	TRANSITION LEVELS	EXCITATION POTENTIAL OF UPPER LEVEL (eV)
C II	24.4			
C III	47.9	5696	$3^1D_2 - 3^1P_1^o$	34.13
N I	14.5			
N II	29.6	5755*	$2p^2 1S_o - 2p^2 1D_2$	4.04
		6357	[$4p^3 P_1 - 3d^3 D_2^o$ $4p^3 P_o - 3d^3 D_1^o$]	25.08
		6548*	$2p^2 1D_2 - 2p^2 3P_1$	1.89
		6584*	$2p^2 1D_2 - 2p^2 3P_2$	1.89
O I	13.6	5577*	$2p^4 1S_o - 2p^4 1D_2$	4.17
		6300*	$2p^4 1D_2 - 2p^4 3P_2$	1.96
		6364*	$2p^4 1D_2 - 2p^4 3P_1$	1.96
O II	35.1	7319*	[$2p^3 2P_{3/2}^o - 2p^3 2D_{5/2}^o$ $2p^3 2P_{1/2}^o - 2p^3 2D_{5/2}^o$]	5.00
		7331*	[$2p^3 2P_{1/2}^o - 2p^3 2D_{3/2}^o$ $2p^3 2P_{3/2}^o - 2p^3 2D_{3/2}^o$]	5.00
O III	54.9	4959*	$2p^2 1D_2 - 2p^2 3P_1$	2.50
		5007*	$2p^2 1D_2 - 2p^2 3P_2$	2.50
Si I	8.1			
Si II	16.3	6347	$4^2P_{3/2}^o - 4^2S_{1/2}$	10.03
		6371	$4^2P_{1/2}^o - 4^2S_{1/2}$	10.02
Si I	10.4			

Table 1 (continued)

ION	IONIZATION POTENTIAL (eV)	$\lambda(\text{\AA})$ OF OBSERVED EMISSION LINE	TRANSITION LEVELS	EXCITATION POTENTIAL OF UPPER LEVEL (eV)
S II	23.4	6286	$4p^4 P_{5/2}^o - 3d^4 D_{5/2}$	16.07
		6306	$4p^4 P_{5/2}^o - 3d^4 D_{7/2}$	16.07
		6717*	$3p^3^2 D_{5/2}^o - 3p^3^4 S_{3/2}^o$	1.84
		6731*	$3p^3^2 D_{3/2}^o - 3p^3^4 S_{3/2}^o$	1.83
S III	35.0	6310*	$3p^2^1 S_o - 3p^2^1 D_2$	3.35
Cl II	23.8			
Cl III	39.9	5517*	$3p^3^2 D_{5/2}^o - 3p^3^4 S_{3/2}^o$	2.24
		5538*	$3p^3^2 D_{3/2}^o - 3p^3^4 S_{3/2}^o$	2.23
Cl IV	53.5	5322*	$3p^2^1 S_o - 3p^2^1 D_2$	4.02
Ar II	27.6			
Ar III	40.9	5191*	$3p^4^1 S_o - 3p^4^1 D_2$	4.11
		7136*	$3p^4^1 D_2 - 3p^4^3 P_2$	1.73
Ar IV	59.8	7169*	$3p^3^2 P_{3/2}^o - 3p^3^2 D_{3/2}^o$	4.33
		7236*	$3p^3^2 P_{3/2}^o - 3p^3^2 D_{5/2}^o$	4.33
		7263*	$3p^3^2 P_{1/2}^o - 3p^3^2 D_{3/2}^o$	4.30
Ar V	75.0	7006*	$3p^2^1 D_2 - 3p^2^3 P_2$	2.01
Kr II	24.6			
Kr III	36.9	6827*	$4p^4^1 D_2 - 4p^4^3 P_2$	1.81

* = Forbidden Transition.

section this provides, the center of the nebula appears devoid of the filamentary structure obvious in the outer regions.

For some planetaries, the spectrographic slit was positioned to cover only the outer regions, as for sample slit position I in Figure 1. This tangential setting integrates over a relatively short pathlength through the nebula. Here, the emission from the filamentary packets and the ambient gas should not be contaminated by the emission from high ionization zones near the central star. NGC 2392, NGC 2440, NGC 3242, NGC 6720, and IC 418 were observed in this manner. For IC 418, no evidence of filamentary structure is visible within its smooth elliptical ring. This is the most distant of the objects in this study. It was included to determine if such nebulae might still provide spectrophotometric evidence for the presence of such structure.

NGC 3587, NGC 6543, and NGC 6826 were studied with the slit positioned as in example II, Figure 1. This affords a comparison of the conditions in the filamentary shell with those of the inner portions of the nebula. For NGC 3587 with its large angular diameter, the slit fell entirely within the inner high ionization zone.

The wavelength range used in the observations runs approximately from $\lambda 4600$ to $\lambda 7400$, varying somewhat with the spectrographic equipment used. Included in this region are both recombination and forbidden emission lines from atoms in various stages of ionization. This allows the filamentary characteristics to be studied for a wide range of emitting species. Table 1 contains a compilation of all lines identified on the spectrograms obtained in this investigation.

Table 2
OBSERVED UNIDENTIFIED LINES

OBSERVED
WAVELENGTH (Å)

5669

6046

6098

6254

6345

6423

6465

6498

6835

6865

6949

6979

7388

Fig. 2 - Sample Emission Lines for Example Slit Settings I and II in Figure 1. θ indicates the direction of movement along these lines corresponding to the angular displacement θ shown in Figure 1.

For each ionic species, this list includes the pertinent ionization potentials along with the laboratory wavelengths of the observed lines (forbidden transitions are denoted in this column by an asterisk), the transitions involved, and the excitation potentials of the upper levels (Allen 1963, Moore 1945). A list of the wavelengths of unidentified emission lines found on some spectrograms is given in Table 2. The measured wavelengths (on the spectrograms) for the unidentified lines are estimated to be uncertain by about $\pm 1 \text{ \AA}$.

The [N II] lines at $\lambda 6548$ and $\lambda 6584$, the [S II] lines at $\lambda 6717$ and $\lambda 6731$, plus the [O I] lines at $\lambda 6300$ and $\lambda 6364$ are of primary interest because of their generic relation to nebular filaments. Therefore these lines were used to determine the positions of filaments along spectral lines for each nebular area studied. Here the spectral lines from the two slit positions seen in Figure 1 would resemble the λ_1 lines in Figure 2. The points along the λ_1 lines designated as filaments are identified by the letter F. The positions on the lines corresponding to the surrounding gas region to be used for comparison with the filamentary packets are marked with the letter S. Where more than one of these features exist for a given nebular area, the letters are followed by Arabic numerals to identify the specific structure referred to.

Finally, the $\lambda 4600$ to $\lambda 7400$ region of the spectrum was chosen because it contains lines useful as temperature and density criteria. The [N II] lines are temperature dependent, as the [O I] would also be if airglow contamination could be eliminated. The observable [S II] and [Cl III] lines serve as density criteria. Thus, the

relative temperatures and densities as well as the emission characteristics of the filaments and the ambient gas are measurable.

Nebular Profiles and Fluxes

Three categories of data were obtained from the photographic spectra: the relative intensity variations for different emitters across the section of the nebula covered by the slit ($I(\lambda, \theta)$), the relative emission line fluxes ($F(\lambda)$) for the points designated by F or S, and the relative temperatures and densities of the F and S regions.

The intensity variations $I(\lambda, \theta)$ across the planetary were obtained from microphotometer traces of selected emission lines. These tracings were made along the lines, perpendicular to the dispersion (i.e. in the vertical direction shown by θ in Figure 2). The scales of the spectrographic slit on the sky and on the spectrograms were used to relate distance along the emission line to displacement in seconds of arc of the slit's projection on the nebula (θ in Figure 1). Thus, the variation in nebular emission was found as a function of both the emission line observed and the angular position within the planetary. Knowing the projection of the slit on the nebula, the separations of the F and S points on the $I(\lambda, \theta)$ graphs were used to identify these features on photographs of the nebula (as shown in Figure 1 for the S and F designations in Figure 2).

Fig. 3 - $I(\lambda, \theta)$ Profiles for the Emission Lines of Figure 2. λ_1 represents the behavior of the nebular line emission of a singly ionized or neutral atom; λ_2 , the auroral line emission of these atoms or a recombination line of H; λ_3 , the forbidden line emission of a highly ionized atom. The Roman numerals refer to the example slit settings shown in Figure 1.

Fig. 4 - Energy Levels for the $2p^2$ Configuration of N^+ .

Mutual contamination of F and S regions occurs. Ambient gas exists both within packets of filaments and also between the packets and the observer. Emission from unresolved, widely spaced filaments probably contributes to the regions marked S. Bearing this complicating factor in mind, a sketch of the expected results in a plot of $I(\lambda, \theta)$ vs θ is presented for low temperature, high density filaments as described by Capriotti (1972a, 1972b) and by Van Blerkom and Arny (1972). Figure 3 shows the $I(\lambda, \theta)$ profiles for the sample nebular lines seen in Figure 2. The filamentary regions should stand out strikingly in certain of the lines of [N II], [S II], [O II], and [O I] as illustrated by the λ_1 line in Figure 3. The forbidden line emission rate is proportional to the second power of the electron density; therefore, the nebular transitions for these ions should show strong dependency on high density filaments. However, the strengths of the auroral lines should not show as great a dependence on density fluctuations according to Capriotti (1972b). The energy level diagram for the [N II] lines observed is shown in Figure 4 as an example of the difference between the auroral and nebular transitions. The nebular lines at $\lambda 6548$ and $\lambda 6584$ are enhanced in the filaments because of the greater abundance of N^+ , the higher density, and the low electron energy (1.89 eV) needed to collisionally excite the 1D_2 level. For the auroral line $\lambda 5755$, the effect of the N^+ abundance increase in the filaments is partially cancelled by the lower electron temperature, i.e. few electrons exist in the filaments with the required energy (4.04 eV) for the excitation of the 1S_0 level. While more high energy electrons are available in the surrounding high

temperature ambient gas, here less nitrogen remains in the singly ionized state. The effect of the N^+ abundance and the effect of the electron energy tend to cancel one another in the case of the auroral transitions. However, there is a slight enhancement of the $\lambda 5755$ line in the filaments since these regions have a higher electron density than the ambient gas. Thus, the auroral lines should show less filamentary concentration than do the nebular lines of the same ion. The expected $I(\lambda, \theta)$ auroral line behavior is shown by the λ_2 profile in Figure 3.

The contours of lines of neutral hydrogen should also have an appearance similar to the λ_2 profile in Figure 3. A change of ionization state should not be a factor here as the hydrogen in both the filaments and in the ambient gas should exist predominately as H^+ . Since the emission rate for recombination lines is proportional to the square of the electron density, the increased density in the filamentary regions causes the moderate intensity enhancement of the H I lines.

The neutral helium lines should exhibit even less dependence on the presence of filaments since helium should exist primarily as He^0 in these features. Some intensity increase in the He I lines could arise from a slight increase in the ambient gas density in the vicinity of filamentary regions. This again is due to the density dependence of the recombination line emission mentioned above. The He II lines should show a negative correlation with filamentary regions because of the expected absence of He^{+2} here.

For slit setting II (see Figure 1), an additional type of $I(\lambda, \theta)$ vs θ profile should appear due to atoms in high states of ionization (i.e. with Strömgren spheres predominately interior to the filamentary regions). This is shown by the λ_3 line in Figure 2 and by the λ_3 profile in Figure 3. The intensity rise in the middle of the line occurs because this is the closest approach of the slit to the central star. Here, the slit integrates over the longest pathlength through the optically thin section of the nebula that it covers. The only sections of the nebula considered optically thick are the condensations themselves, which, with their associated filaments, account for only a small fraction of the central surface area of the nebula.

Relative fluxes were obtained from intensity vs wavelength traces of the spectrograms. A short microphotometer slit was used to isolate each region designated by F or S (as indicated by the arrows in Figure 2) for all lines, then to trace across the spectrographic plate in the wavelength direction. The measured intensities were converted to relative fluxes using observations of the standard stars of Hayes (1970) through the relation

$$F_{\lambda}^N = \frac{I_{\lambda}^N}{I_{\lambda}^S} F_{\lambda}^S \cdot R \quad (2)$$

where F_{λ}^N is the relative flux of the nebular emission lines, F_{λ}^S is the standard star flux from Hayes, I_{λ}^N is the observed nebular line intensity, and I_{λ}^S is the observed standard star continuum intensity.

R is a correction for differential atmospheric extinction between the standard star and the nebular observations, where

$$R = 10^{-0.4a_{\lambda}(\sec Z_N - \sec Z_S)}. \quad (3)$$

In the above equation, a_{λ} is the atmospheric extinction coefficient as a function of wavelength for the observatory, while Z_S and Z_N are the zenith distances of the star and of the nebula, respectively, at the time of their observation. The values of the atmospheric extinction coefficients for Lowell Observatory were provided by White (1970) and Baumert and Wing (1970), while those for Mt. Palomar were taken from Oke (1965).

A long slit microphotometer tracing of each spectrum was also analyzed using equation (2). This leads to a set of relative fluxes approximating an average over an area of the nebula large compared to the regions represented by the F or the S relative fluxes (strictly speaking, the long slit averages transmission, not flux). The sets of average fluxes are denoted by the letter A. These fluxes were then normalized to the flux of H β equalling 100, as equation (2) yields only relative fluxes within a spectrum. This normalization was done on the basis of the A fluxes for ease of comparison with previous studies, since these fluxes averaged over the area covered by the slit most nearly relate to the integrated fluxes observed photoelectrically. The normalizing factor thus derived was applied to the F and S sets of relative flux values from the same spectrum as each A flux. Normalizing the regional relative fluxes to each short slit value of H β equalling 100 would have obscured the changes

Fig. 5 - Theoretical [S II] Line Ratios.

Here $r_1 = \frac{F_c(\lambda 6717)}{F_c(\lambda 6731)}$ from Krueger, Aller and Czyzak (1970),
 $x = 10^{-4} N_e t^{-1/2}$, and $t = 10^{-4} T_e$.

in the flux from H β that occur in going from one region to the next. For an observed nebula not yielding a reliable value for H β , the A fluxes were normalized to available photoelectric data.

Temperature and Density Determination

For the fluxes of certain lines to be used as temperature or density criteria, it was necessary to apply an interstellar reddening correction in accordance with the relation

$$\log F_c(\lambda) = \log F(\lambda) + c f(\lambda) \quad (4)$$

where $F_c(\lambda)$ is the corrected relative flux for an observed flux $F(\lambda)$, c is the extinction coefficient for the nebula from Cahn and Kaler (1971), and $f(\lambda)$ is the reddening function taken from Seaton (1960).

The lines of [S II] and [N II] provide the primary criteria in the analysis of filamentary densities and temperatures. The density criterion is the ratio of the [S II] lines, where

$$r_1 = \frac{F_c(\lambda 6717)}{F_c(\lambda 6731)} \quad (5)$$

The theoretical values of r_1 are given by Krueger, Aller, and Czyzak (1970), from whose calculations the curves in Figure 5 were plotted. Throughout, the standard definitions

$$x = 10^{-4} N_e t^{-1/2} \quad (6)$$

Fig. 6 - Theoretical [N II] Line Ratios.

$$\text{Here } r_2 = \frac{F_c(\lambda 6548) + F_c(\lambda 6584)}{F_c(\lambda 5755)} = \frac{8.5 \times 10^{1.08/t}}{1 + 0.29x},$$

$$x = 10^{-4} N_e t^{-1/2}, \text{ and } t = 10^{-4} T_e.$$

Fig. 7 - Sample T_e vs N_e Curves from $[S II]$ and $[N II]$ Line Ratios.

and

34

$$t = 10^{-4} T_e \quad (7)$$

are used. These curves show the r_1 vs $\log x$ behavior for a range of t values common to planetary nebulae. The [N II] temperature criterion,

$$r_2 = \frac{F_c(\lambda 6548) + F_c(\lambda 6584)}{F_c(\lambda 5755)} = \frac{8.5 \times 10^{1.08/t}}{1 + 0.29x}, \quad (8)$$

from Aller and Czyzak (1968) was used to generate the curves in Figure 6, which show the $\log r_2$ vs $\log x$ behavior, again, for a range of t values common to planetary nebulae.

For each nebular region, the observed r_1 and r_2 ratios, when applied to Figures 5 and 6, respectively, together yielded a pair of curves in the temperature (T_e)-density (N_e) plane. The intersection of the [N II] generated curve with the [S II] generated curve determines the temperature and density of this region. See Figure 7.

For the filaments to be in pressure equilibrium with the surrounding gas, the electron pressures of the two regions must be equal, the electron pressure being

$$p_e = k N_e T_e. \quad (9)$$

In order for this condition to hold, the F to S region temperature ratio must equal the inverse of the density ratio.

A problem exists in applying r_2 to filaments in that [N II] $\lambda 5755$ is an auroral transition. As previously discussed, this line

Fig. 8 - Theoretical [Cl III] Line Ratios.

Here $r_3 = \frac{F_c(\lambda 5517)}{F_c(\lambda 5538)}$ from Krueger, Aller, and Czyzak (1970), $x = 10^{-4} N_e t^{-1/2}$, and $t = 10^{-4} T_e$.

may to a certain extent tend to reflect the conditions in the higher temperature ambient gas, even when r_2 is determined from F region fluxes. Thus, the temperatures derived for filamentary regions from the r_2 ratio may be upper limits only.

For [Cl III] lines, the ratio

$$r_3 = \frac{F_c(\lambda 5517)}{F_c(\lambda 5538)} \quad (10)$$

serves as a density criterion for the regions surrounding the filaments, as Cl^{+2} represents an ionization state too high to be likely to exist in a filament. Again, the theoretical values for r_3 are taken from Krueger, Aller, and Czyzak (1970). A plot of r_3 vs. $\log x$ for a range of t values can be found in Figure 8.

The theoretical r_4 values for the [O I] lines

$$r_4 = \frac{F_c(\lambda 6300) + F_c(\lambda 6364)}{F_c(\lambda 5577)} \quad (11)$$

were developed with the hope of using this ratio as an additional temperature criterion. However, it did not prove possible to separate adequately the nebular components from the airglow contributions to these lines.

The $I(\lambda, \theta)$ and the $F(\lambda)$ data are used along with the derived temperatures and densities to provide an observational description of the filamentary structure of planetary nebulae.

Chapter 3

DATA AND RESULTS

Nebular Observations

With the exception of the NGC 6543 spectrograms, all spectrographic plates were taken at Lowell Observatory, Flagstaff, Arizona. The observations were done at the 72-in. Perkins reflector using the Carnegie Image Tube in the DTM Spectrograph No. 3. The NGC 6543 plates were taken with the coudé spectrograph at the 200-in. telescope of the Hale Observatories.

Table 3 is a compilation of the pertinent observational data for the eight nebulae studied. For NGC 2392 and NGC 2440 two separate areas of each nebula were observed, and these are differentiated by the Roman numerals I and II following the NGC designation. Thus, a total of ten nebular areas are included in this investigation. In Table 3, column (1) lists each nebula's NGC or IC number, plus the appropriate Roman numeral where necessary. Columns (2) and (3) list the extinction coefficient c and the distance r (in kiloparsecs), respectively, for each nebula as taken from the values of Cahn and Kaler (1971). Column (4) gives the nebular regions studied, where, as defined in the previous chapter, A denotes an average over the area covered by the slit, F, the filamentary regions, and S, the surrounding gas. The remaining four columns list, respective-

Table 3

NEBULAR OBSERVATIONAL DATA

NEBULA	c	r (kpc)	NEBULAR REGIONS ANALYZED	PLATE; DATE TAKEN	WAVELENGTH RANGE (Å); EMULSION	DISPERSION (Å/mm)	EXPOSURE TIMES (hrs: min)
IC 418	0.38	1.71	A	16B, C, D 1/22/71	4800 to 7400 Baked IIIa-J	98	0:10, 0:30, 3:45
				27B, C 1/27/71	5750 to 7250 Baked IIa-0	47	0:30, 1:00
NGC 2392 I	0.56	1.09	A, F, S	21B, C, D 1/24/71	4800 to 7400 Baked IIIa-J	98	0:30, 1:00, 3:00
NGC 2392 II	0.56	1.09	A, F, S	25B, C 1/26/71	5750 to 7250 Baked IIa-0	47	0:30, 2:30
NGC 2440 I	1.35	0.97	A, F1, F2, F3, S	19B, C, D 1/23/71	4800 to 7400 Baked IIIa-J	98	0:30, 1:00, 3:00
NGC 2440 II	1.35	0.97	A, F, S	23B, C 1/25/71	5750 to 7250 Baked IIa-0	47	0:30, 3:00
NGC 3242	0.23	0.97	A, F, S	14B, C 1/22/71	4800 to 7400 Baked IIIa-J	98	0:45, 3:35
				18B, C 1/23/71	4800 to 7400 Baked IIa-0	98	0:45, 1:30
				26A, B 1/27/71	5750 to 7250 Baked IIa-0	47	0:30, 2:00

Table 3 (continued)

NEBULAR OBSERVATIONAL DATA

NEBULA	c	r (kpc)	NEBULAR REGIONS ANALYZED	PLATE; DATE TAKEN	WAVELENGTH RANGE (Å); EMULSION	DISPERSION (Å/mm)	EXPOSURE TIMES (Hrs: min)
NGC 3587	0.15	0.52	A	20B, C 1/24/71	4800 to 7400 Baked IIIa-J	98	0:30, 2:00
				22B, C 1/25/71	4800 to 7400 Baked IIa-0	98	0:30, 2:35
				24 1/26/71	5750 to 7250 Baked IIa-0	47	3:00
NGC 6543	0.25	1.50	A, F1, F2, S	Pd 12387 8/8/71	4800 to 7000 098-01	27	6:10
				Pd 12393 8/10/71	4800 to 7000 098-01	27	0:34
NGC 6720	0.36	0.73	A, F1, F2, F3, S1, S2	4A, B 8/9/70	5500 to 7200 Baked IIa-0	32	0:01, 0:30
NGC 6826	0.48	1.08	A, F, S	10C, D 8/12/70	4650 to 6350 Baked IIa-0	32	0:05, 1:00
				12A, B 8/12/70	5500 to 7200 Baked IIa-0	32	0:05, 1:02

Fig. 9 - Sample Nebular Spectra.

Plate I - Nebular Slit Positions.

ly, the plate designation and the date of observation, the wavelength range and the type of emulsion used, the reciprocal linear dispersion in $\text{\AA}/\text{mm}$, and the exposure times.

A sample spectrum (from $\lambda 6300$ to $\lambda 6731$) for each of the ten nebular areas is shown in Figure 9. The F and S regions identified for each nebular area are indicated by the arrows at the left of each spectrum. These arrows also point to the line along which the short slit microphotometer traces of the spectra were made (for the determination of the $F(\lambda)$ values of these regions). The bar on the end of the arrow appearing on the right of each spectrum indicates the approximate length of the microphotometer slit used in long slit tracings. These traces were used to derive the average fluxes for the whole area (A values) of the nebula covered by the slit.

Direct photographs (Curtis 1918, Perek and Kohoutek 1967, Aller 1969) of the observed planetaries are presented in Plate I. The distance between the spectrographic slit and the central star was measured using the offset guidebox. From this measured offset, the position of the projection of the slit on each nebula was determined. Plate I shows these projections, with the Roman numeral designations included for the nebulae in which two separate areas were studied. For NGC 2440, in which no central star is seen, the middle of the bright region in the nebula's center served as the offset reference point. The F and S regions defined in Figure 9 are identified with the sections of the planetaries to which they correspond. This was done with the aid of their measured separations taken from the $I(\lambda, \theta)$ contours presented later in this chapter.

$I(\lambda, \theta)$ Data Reduction and Errors

Certain inaccuracies are introduced into the $I(\lambda, \theta)$ data observationally. Seeing changes alter the apparent size and peak intensity of filamentary features on the spectrograms. As an example, in one exposure, a nebular line contour may indicate an filamentary feature to be about 5" of arc in size; and, an auroral line may indicate that the same feature is 10" of arc. In another exposure of the same nebular area, the aforementioned feature has an apparent size of 6" of arc from the nebular line contour and 12" of arc from the auroral line contour. Therefore, for the sake of intercomparison of the same nebular structure in different lines, $I(\lambda, \theta)$ vs θ positional traces were made, as far as possible, only of lines within the same spectrum denoting a particular slit setting. No intercomparison was made of features in different spectra, since only in a given spectrum would one expect all of the lines to be identically affected by seeing conditions. Thus, while the $I(\lambda, \theta)$ contours show the relative nebular structure for various emitters, these profiles do not yield absolute small scale details because of seeing effects.

The positional traces, plus the traces in wavelength (which will be discussed later) from which the $F(\lambda)$ data are derived, were made on a Grant Instruments' Mark III Comparator - Microphotometer. The major problem encountered here is that this microphotometer was designed to trace in the wavelength direction. While it is possible to shorten the slit adequately for wavelength traces, a different

situation exists in positional tracing. For the microphotometer carriage to drive the slit along the lines instead of across them, the plate must be placed so that the length of the lines is at a right angle to the length dimension of the slit. The slit length cannot be adjusted to extremely small sizes. This meant that, for the positional traces, the microphotometer slit was occasionally wider than the line being traced. The effect of this inclusion of some clear plate in the line tracing is to moderate the intensity variations along the line. While true intensity distributions are not attainable from these traces, the slit imposed limitation is not severe enough to obscure the major emission trends for the $I(\lambda, \theta)$ data.

The scale for the microphotometer tracings was obtained in the following manner. Since the comparison star spectra were trailed the length of the spectrographic slit, the measured widths of these spectra were used to determine the slit to plate scale factor. The scale of the slit on the sky is known so that the number of seconds of arc on the sky corresponding to a millimeter along a spectral line could be found for each spectrogram. Using this information, the scale of the traces was then determined from the drive rate used for the microphotometer carriage.

In the positional transmission traces, plate grain noise because of the small slit led to uncertainties in the clear plate level and in the exact shape of the nebular contours. This led in turn to errors in the relative intensities along the profiles as determined from transmission-relative intensity data (the determination

of these data is discussed in the next section). For the final presentation of the $I(\lambda, \theta)$ vs θ data (e.g. as in Figure 10), different intensity scales were used for the sake of ease in comparison of lines having widely different strengths. The intensity values shown for these nebular profiles, then, do not reflect the relative strengths of the emission lines, but rather the relative contours of the nebula when seen in the light of these various lines.

Overall, an estimate can be made of the uncertainty in the θ positions for structural features. This turns out to be about 1" of arc. Likewise, the error in the relative intensity along an $I(\lambda, \theta)$ contour is estimated to be on the order of a few percent.

F(λ) Data Reduction and Errors

The transmission-intensity data were obtained from intensity strip calibration plates. The strips on these plates are composed of sections formed by exposure to light of different calibrated intensities. Filters permit the light source to emit at the same wavelength as the image tube's phosphor screen ($\lambda 4400$). A calibration plate was developed with each spectrogram to avoid errors in the conversion of transmission to intensity arising from variations in the developing process.

The values of the transmission for the segments of the calibration plate strips were measured from traces of these plates. From the set of relative intensities, I_R , given for the DTM calibration plate apparatus, transmission vs $\log I_R$ curves were drawn.

The $\log I_R$ values were evenly spaced along the abscissa, facilitating the fitting of a smooth curve to the data points. This averaged out the effect of errors in the measured transmission values of the calibration plates due to grain noise and drift in the microphotometer sensitivity. Since the image tube's phosphor screen emits light at only one color, just one transmission - $\log I_R$ curve was required to convert transmission to intensity for the entire wavelength range of each spectrum observed with the DTM spectrograph.

These intensity strip calibration plates were illuminated for an hour each, commensurate with the nebular exposure times. However, the data from these plates were also applied to the spectra of the comparison stars which were from four to ten minutes in length. A test was conducted to check for possible reciprocity problems. A six minute exposure on the wedge standard plate apparatus at the 72-in. Perkins reflector was developed with one of the intensity strip calibration plates. Both plates were from the same batch of baked IIA-0 plates. The linear portions of the resulting transmission - $\log I_R$ curves were found to have identical slopes, indicating lack of reciprocity failure for these exposures which are commensurate with the exposure times of the stellar and nebular spectra.

The linear portions of the transmission - $\log I_R$ curves were used to generate direct intensity traces of the stellar and nebular spectra with the microphotometer. The use of only the linear sections ensured that no overexposed or underexposed lines were analyzed.

Some inconsistency in the positioning of the microphotometer slit may occur in the tracing (in wavelength) of a single feature as it appears in spectra of different exposures for a given nebular area. However, the effect of this and of changes in the microphotometer sensitivity over the time required to trace a set of spectra were found to be negligible. Two traces were made of the same section of a spectrum, one just after the machine had warmed up and the second after it had been running for three hours. Each trace yielded the same relative areas for the emission lines present.

The nebular emission lines were identified with the aid of a catalogue by Meinel, Aveni, and Stockton (1969). The continuum and the line profiles were sketched on the traces. Then, the areas of the emission lines were measured using a compensating polar planimeter. A correction for a small variation in the dispersion across the plate was applied to these areas. The greatest uncertainty introduced here affects the weak lines more than it does the strong and intermediate lines. This is the uncertainty in the continuum position on the tracings due to grain noise. While the average error in the continuum position is the same for lines of all strengths, this error affects a greater fraction of the measured area of a weak line than it does of a strong line.

The wavelength positions of the observed nebular emission lines were located on the comparison star traces. The continuum intensities of these points were measured in the same area units used for the emission lines. Neutral density filters were necessary in taking the stellar spectrograms because of the apparent bright-

ness of these objects and the sensitivity of the image tubes. Since these filters were not used for the fainter nebulae, the observed intensities of the stellar continua had to be corrected for the wavelength response of the filters. The observed emission line and the stellar continuum intensities are compared in equation (2). Thus the other system responses (e.g. those of the image tube and the other filters) cancel as the correction factors are the same for both the star and the nebula for a given wavelength. Equations (2) and (3) were applied to the nebular and stellar data through the use of a computer program and the resulting $F(\lambda)$ values were then normalized.

No corrections for weakening of the emission lines due to underlying terrestrial atmospheric absorption bands were deemed necessary based on the relatively weak strengths listed for these features in Moore, Minnaert, and Houtgast (1966).

The uncertainty in the $F(\lambda)$ values for strong and intermediate lines, resulting from the sources of error discussed in this section, is estimated to be about 10 per cent, while the error in weak lines appears to be on the order of 25 per cent.

Good exposures were available for the lines used in the determinations of T_e and N_e . The 10 per cent uncertainty in the $F(\lambda)$ values leads to a maximum uncertainty of 40 per cent in the N_e values based on the r_1 and r_3 ratios, and a maximum uncertainty of 15 per cent in the T_e values based on the $\log r_2$ ratio. In some cases for the r_2 ratio, the $\lambda 6584$ line was overexposed. Here, the $F(\lambda 6584)$

value was estimated from the flux of the $\lambda 6548$ line and the Einstein coefficients for these two transitions found in Wiese, Smith, and Glennon (1966).

Line Contours, Fluxes, Temperatures, and Densities

The results of the photographic spectrophotometry are presented in this section for the ten observed nebular areas. The data are given in sets, by nebular area, in the order in which they will be discussed in Chapter 4. Each set consists of a figure containing the $I(\lambda, \theta)$ contours, a table of the $F(\lambda)$ values for the structural regions studied, and a table of the T_e and N_e data for these regions.

The $I(\lambda, \theta)$ contours are given as plots of relative intensity vs angular position, θ , on the nebula for each available emission line. These intensities are uncorrected for airglow contamination, atmospheric extinction, or interstellar extinction. The positions on the contours of the structural features identified in Figure 9 are indicated by arrows. These arrows are labeled with their previously assigned F and S designations.

Several spectrograms were taken for each of the ten nebular areas. Thus, more than one set of emission line fluxes resulted for the F, S, and A regions of a given area. The flux values for each line in each region were averaged. This gave a single set of line fluxes for the F, S, and A regions of each nebular area. These relative fluxes are tabulated in columns labeled as to the region

studied. For example, a column headed by an F designation includes the relative flux values from that nebular area's filamentary region. For comparison, a column containing available photoelectric data is included in each table. The flux values are corrected for extinction by the earth's atmosphere, but not for interstellar extinction.

The T_e and N_e information is given in the last table of each data set. These tables include the value of the reddening function ($f(\lambda)$ from Seaton 1960) for each necessary line and the regional fluxes for these lines corrected for interstellar extinction. The resulting r_1 , $\log r_2$, and r_3 ratios appear here in a section under the corrected fluxes. Their values are given in the columns of the structural region to which they apply. The r_3 values come from the [Cl III] $\lambda\lambda 5517$ and 5538 fluxes averaged over both F and S regions. This average r_3 is applied only to the surrounding gas as no Cl^{+2} is expected to exist in the filaments. The N_e and T_e values, derived from these ratios as described in Chapter 2, are the last numbers appearing at the bottom of each of these tables. The values from the intersection of T_e vs N_e curves of [S II] and [N II] are labeled (r_1, r_2) , while the values from [N II] and [Cl III] are labeled (r_2, r_3) . An X in the T_e or N_e space of an F or S column indicates that either the criterion is not applicable to that region or the necessary line fluxes were not available. When r_2 was inaccessible, the average N_e for the range covered by the T_e vs N_e curves for r_1 and r_3 is given (these average values are designated

by $\overline{N_e(r_1)}$ and $\overline{N_e(r_3)}$). The T_e dependency of these latter two ratios is small, as can be seen by the steepness of the [S II] curve in Figure 7.

Fig. 10 - $I(\lambda, \theta)$ Contours for NGC 3242.

Table 4

F(λ) DATA FOR NGC 3242^a

λ (Å)	IDENT.	F	S	A	PHOTOELECTRIC DATA ^b
4861	H β	B	93.8	100.0	100
4959	[O III]	B	B	B	420
5007	[O III]	B	B	B	1280
5191	[Ar III]	0.4	---	---	---
5412	He II	---	0.3	---	2.8
5517	[Cl III]	1.1	0.9	0.9	---
5538	[Cl III]	0.9	1.1	0.8	---
5577	[O I]NNS	7.2	5.2	6.0	---
5755	[N II]	0.6	0.3	0.3	---
5876	He I	24.1	19.0	18.8	11.2
5932	He II	---	---	0.5	---
6005	He II	---	---	0.2	---
6098		0.6	0.6	0.7	---
6234	He II	0.6	0.6	0.8	---
6286	S II	0.3:	0.1:	0.3:	---
6300	[O I]NNS	3.3	1.1	1.9	---
6306	S II	0.4	0.4:	---	---
6310	[S III]	2.0	1.6	1.6	---

Table 4 (continued)

$\lambda(\text{\AA})$	IDENT.	F	S	A	PHOTOELECTRIC DATA ^b
6357	N II	0.4	0.1:	---	---
6364	[O I]NNS	1.2	0.5	0.6	---
6423		0.6	---	0.6	---
6465		1.0	1.3	0.9	---
6548	[N II]	8.3	4.0	6.0	---
6563	H α	B	B	B	---
6584	[N II]	21.8	5.5	10.5	---
6678	He I	10.3	10.1	8.6	---
6717	[S II]	2.6	0.9	1.4	---
6731	[S II]	3.4	0.9	1.6	---
6827	[Kr III]	0.7	1.4	1.6	---
6835		0.5	1.2	1.3	---
6865		1.2	1.6	1.4	---
6949		---	2.0	1.1	---
7065	He I	7.1	6.2	6.7	---
7136	[Ar III]	15.9	15.4	14.6	2.7
7236	[Ar IV]	1.6	2.1	3.2	---
7263	[Ar IV]	0.9:	1.7	2.9	---
7319	[O II]	---	---	0.9:	---
7331	[O II]	---	---	1.3:	---

^aExplanation of symbols used: --- = not measurably present,
NNS = nebular-night sky line blend, : = uncertain value,
B = overexposed, f = masked by plate flaw.

^bAller and Czyzak (1972).

Table 5
 N_e , T_e DATA FOR NGC 3242

$\lambda(\text{\AA})$	IDENT.	$f(\lambda)$	F	S
6717	[S II]	-.400	2.1	0.7
6731	[S II]	-.403	2.7	0.7
5755	[N II]	-.211	0.5	0.2
6548	[N II]	-.368	6.8	3.3
6584	[N II]	-.377	17.9	4.5
5517	[Cl III]	-.158	1.0	1.0
5538	[Cl III]	-.163	0.8	0.8
		$r_1 =$	0.78	1.00
		log $r_2 =$	+1.69	+1.59
		$r_3 =$	X	1.00
		$N_e(r_1, r_2)$ in cm^{-3}	= 5500	2200
		$T_e(r_1, r_2)$ in $^{\circ}\text{K}$	= 13100	15500
		$N_e(r_2, r_3)$ in cm^{-3}	= X	3500
		$T_e(r_2, r_3)$ in $^{\circ}\text{K}$	= X	15300

Fig. 11 - $I(\lambda, \theta)$ Contours for NGC 2392 I.

Table 6
F(λ) DATA FOR NGC 2392 I^a

$\lambda(\text{\AA})$	IDENT.	F	S	S	PHOTOELECTRIC DATA ^b
4861	H β	138.7	75.5	100.0	100
4959	[O III]	B	B	B	352
5007	[O III]	B	B	B	1451
5191	[Ar III]	0.7	0.4	0.4	1.3
5412	He II	2.2	2.7	2.2	1.2
5517	[Cl III]	0.9	0.6	0.6	---
5538	[Cl III]	0.7	0.7	0.4	---
5577	[O I]NNS	1.8	1.8	1.7	---
5755	[N II]	1.3	0.6	0.6	---
5876	He I	4.3	2.3	2.9	7.2
6300	[O I]NNS	2.8	1.8	1.8	2.7
6310	[S III]	2.8	1.6	1.5	
6364	[O I]NNS	1.2	0.6	0.5:	---
6548	[N II]	111.6	24.3	43.9	---
6563	H α	B	B	B	443
6584	[N II]	326.6	66.9	118.6	
6678	He I	f	0.9:	1.3	1.1
6717	[S II]	10.0	5.2	6.6	4.9
6731	[S II]	11.7	5.1	8.2	
7136	[Ar III]	8.1	6.8	6.7	5.9

^a Explanation of symbols used: --- = not measurably present, NNS = nebular-night sky line blend; : = uncertain value, B = overexposed, f = masked by plate flaw.

^b Aller, Boeshaar, and Czyzak (1972).

Table 7
 N_e , T_e DATA FOR NGC 2392 I

$\lambda(\text{\AA})$	IDENT.	$f(\lambda)$	F	S
6717	[S II]	-.400	6.0	3.1
6731	[S II]	-.403	7.0	3.0
5755	[N II]	-.211	1.0	0.5
6548	[N II]	-.368	69.4	15.1
6584	[N II]	-.377	200.9	41.1
5517	[Cl III]	-.158	0.7	0.5
5538	[Cl III]	-.163	0.6	0.6
	$r_1 =$		0.86	1.03
	log $r_2 =$		+2.43	+2.05
	$r_3 =$		X	1.00
$N_e(r_1, r_2)$ in cm^{-3}	$=$		3600	1900
$T_e(r_1, r_2)$ in $^{\circ}\text{K}$	$=$		6800	9300
$N_e(r_2, r_3)$ in cm^{-3}	$=$		X	3400
$T_e(r_2, r_3)$ in cm^{-3}	$=$		X	9200

Fig. 12 - $I(\lambda, \theta)$ Contours for NGC 2392 II.

Table 8
F(λ) DATA FOR NGC 2392 II^a

λ (Å)	IDENT.	F	S	A	PHOTOELECTRIC DATA ^b
5755	[N II]	f	1.2	0.6	---
5876	He I	7.2	4.5	2.9	7.2
6234	He II	0.3	0.4	0.1	---
6300	[O I]NNS	18.4	5.6	6.7	2.7
6310	[S III]	4.1	1.9	1.8	
6364	[O I]NNS	4.4	1.6	1.8	---
6498		f	---	0.4	---
6548	[N II]	B	13.5	11.2	443
6563	H α	B	B	B	
6584	[N II]	B	27.3	27.1	
6678	He I	4.5	2.2	2.3	1.1
6717	[S II]	33.5	7.4	7.1	4.9
6731	[S II]	36.0	7.3	7.4	
6827	[Kr III]	0.9	0.7	0.7	---
6835		0.5	0.5	0.3	---
6865		1.2	0.7	0.7	---
7065	He I	4.1	1.8	1.2	---
7136	[Ar III]	8.6	5.1	4.1	5.9

^a Explanation of symbols used: --- = not measurably present,
NNS = nebular-night sky line blend, : = uncertain value,
B = overexposed, f = masked by plate flaw.

^b Aller, Boeshaar, and Czyzak (1972).

Table 9

 N_e, T_e DATA FOR NGC 2392 II

$\lambda(\text{\AA})$	IDENT.	$f(\lambda)$	F.	S.
6717	[S II]	-.400	20.0	4.4
6731	[S II]	-.403	21.4	4.3
5755	[N II]	-.211	X	0.9
6548	[N II]	-.368	X	8.4
6584	[N II]	-.377	X	16.8
		$r_1 =$	0.93	1.02
		$\log r_2 =$	X	1.45
		$\overline{N_e(r_1)} \text{ in cm}^{-3} =$	2800	X
		$N_e(r_1, r_2) \text{ in cm}^{-3} =$	X	2100
		$T_e(r_1, r_2) \text{ in } ^\circ\text{K} =$	X	19800

Fig. 13 - $I(\lambda, \theta)$ Contours for NGC 2440 I.

Table 10
F(λ) DATA FOR NGC 2440 I^a

λ (Å)	IDENT.	F-1	F-2	F-3	S	A	PHOTOELECTRIC DATA ^b
4861	H β	142.5	216.4	245.2	34.2	100.0	100
4959	[O III]	674.5	1107.1	1433.1	156.1	287.8	460
5007	[O III]	B	B	B	346.2	662.0	1411
5191	[Ar III]	87.2	41.9	22.7	---	29.5	---
5412	He II	---	---	7.3:	12.3	2.0:	---
5577	[O I]NNS	57.9	50.6	56.2	60.2	49.8	---
5755	[N II]	35.2	25.6	27.4	12.8	24.3	---
5876	He I	33.0	29.3	24.3	8.1:	20.6	18.4
6234	He II	---	---	12.3	12.7	7.6:	---
6300	[O I]NNS	80.4	41.6	37.6	16.6	45.4	46.0
6364	[O I]NNS	35.9	11.4:	8.6:	---	16.8	14.8
6548	[N II]	1507.0	890.3	788.3	411.8	635.7	---
6563	H α	778.1	867.7	834.3	314.7	411.4	---

Table 10 (continued)

$\lambda(\text{\AA})$	IDENT.	F-1	F-2	F-3	S	A	PHOTOELECTRIC DATA ^b
6584	[N II]	B	B	B	943.1	1801.0	---
6717	[S II]	174.4	99.4	91.0	63.4	84.3	} 57.0
6731	[S II]	173.0	118.0	79.5	46.5	83.5	

^a Explanation of symbols used: --- = not measurably present, NNS = nebular-night sky line blend, : = uncertain value, B = overexposed, f = masked by plate flaw.

^b Aller and Czyzak (1972).

Table 11

 N_e, T_e DATA FOR NGC 2440 I

$\lambda(\text{\AA})$	IDENT.	$f(\lambda)$	F-1	F-2	F-3	S
6717	[S II]	-.400	50.3	28.7	26.2	18.3
6731	[S II]	-.403	49.4	33.9	22.7	13.3
5755	[N II]	-.211	18.3	13.3	14.2	6.6
6548	[N II]	-.368	480.1	283.6	251.1	131.2
6584	[N II]	-.377	1416.2*	836.6*	740.8*	292.2
		$r_1 =$	1.02	0.85	1.15	1.38
		$\log r_2 =$	+2.01	+1.93	+1.84	+1.81
		$N_e(r_1, r_2) \text{ in cm}^{-3} =$	2000	4000	1200	200
		$T_e(r_1, r_2) \text{ in } ^\circ\text{K} =$	9600	10200	11500	13800

* From $\lambda 6548$ Flux Values and Einstein Coefficients.

Fig. 14 - $I(\lambda, \theta)$ Contours for NGC 2440 II.

Table 12
F(λ) DATA FOR NGC 2440 II^a

λ (Å)	IDENT.	F	S	A	PHOTOELECTRIC DATA ^b
5755	[N II]	24.9	12.9	15.5	---
5876	He I	23.3	11.7	17.1	18.4
6234	He II	5.1	8.2	4.4	---
6254		4.3	---	2.2:	---
6286	S II	3.9	---	1.3:	---
6300	[O I]NNS	242.4	38.4	57.2	46.0
6310	[S III]	7.5	2.0:	3.3	---
6347	Si II	5.1	---	2.0:	---
6357	N II	3.8	---	1.9:	---
6364	[O I]NNS	50.8	9.9	17.1	14.8
6498		10.4	5.3	4.7	---
6548	[N II]	B	431.6	595.6	---
6563	H α	B	309.9	494.7	---
6584	[N II]	B	B	B	---
6678	He I	30.4	11.7	14.9	---
6717	[S II]	280.1	73.0	71.2	} 57.
6731	[S II]	315.7	56.4	85.2	
6827	[Kr III]	20.0	17.0	15.0	---
6835		9.6	11.6	9.3	---
6865		16.3	27.5	16.8	---
6949		19.2	36.2	19.7	---
6979		7.8:	13.8:	10.0:	---
7065	He I	24.3	---	---	---
7136	[Ar III]	42.0	---	30.7	60

^a Explanation of symbols used: --- = not measurably present,
NNS = nebular-night sky line blend, : = uncertain value,
B = overexposed, f = masked by plate flaw.

^b Aller, Boeshaar, and Czyzak (1972).

Table 13

F(λ) DATA FOR NGC 2440 II

$\lambda(\text{\AA})$	IDENT.	$f(\lambda)$	F	S
6717	[S II]	-.400	80.8	21.1
6731	[S II]	-.403	90.2	16.1
5755	[N II]	-.211	X	6.7
6548	[N II]	-.368	X	137.5
6584	[N II]	-.377	X	405.6*
		$r_1 =$	0.90	1.31
	log	$r_2 =$	X	1.91
	$\overline{N_e(r_1)}$ in cm^{-3}	=	3200	X
	$N_e(r_1, r_2)$ in cm^{-3}	=	X	500
	$T_e(r_1, r_2)$ in $^{\circ}\text{K}$	=	X	10800

* from $\lambda 6548$ Flux Value and Einstein Co-efficients.

Fig. 15 - $I(\lambda, \theta)$ Contours for NGC 6720.

Table 14
F(λ) DATA FOR NGC 6720^a

λ ($\text{\AA}$)	IDENT.	F-1	F-2	F-3	S-1	S-2	A	PHOTOELECTRIC DATA ^b
5876	He I	5.4:	4.0:	X	4.6:	X	7.5	7.5
6300	[O I]NNS	101.6	12.7	10.1	5.6:	3.4:	15.9	41.1
6364	[O I]NNS	9.5	---	---	---	---	5.7:	---
6548	[N II]	B	531.6	621.9	475.3	310.3	635.0	1051
6563	H α	B	508.8	B	647.6	B	B	
6584	[N II]	B	659.6	753.8	424.0	424.0	B	
6717	[S II]	77.6	17.9:	12.7:	22.4	11.9:	41.1	48.1
6731	[S II]	101.1	21.4:	20.7:	16.1:	7.7:	30.6	

^a Explanation of symbols used: --- = not measurably present, NNS = nebular-night sky line blend, : = uncertain value, B = overexposed, f = masked by plate flaw.

^b Aller, Boeshaar, and Czyzak (1972).

Table 15

 N_e, T_e DATA FOR NGC 6720

$\lambda(\text{\AA})$	IDENT.	$f(\lambda)$	F-1	F-2	F-3	S-1	S-2
6717	[S II]	-.400	55.7	12.8	9.1	16.1	8.5
6731	[S II]	-.403	72.4	15.3	14.8	11.5	5.5
	$r_1 =$		0.77	0.84	0.61	1.40	1.55
	$\overline{N_e(r_1)} \text{ in cm}^{-3} =$		5400	4000	11000	200	X

Fig. 16 - $I(\lambda, \theta)$ Contours for NGC 6543.

Table 16
F(λ) DATA FOR NGC 6543^a

λ (Å)	IDENT.	F-1	F-2	S	A	PHOTOELECTRIC DATA ^b
4861	H β	99.6	32.4	113.9	100.0	100
4922	He I	0.8	---	---	0.6	
4959	[O III]	164.5	74.7	B	216.4	229
5007	[O III]	B	B	B	B	671
5016	He I	1.2	---	---	1.4	
5538	[Cl III]	0.3	---	---	0.2	
5755	[N II]	0.6	---	---	0.2	
5876	He I	11.9	3.7	14.3	12.8	
6300	[O I]NNS	1.3	0.2	---	0.3	
6310	[S III]	0.7	0.3	0.4	0.6	
6364	[O I]NNS	0.3	---	---	0.1:	
6548	[N II]	20.3	8.2	2.4	7.0	
6563	H α	B	B	B	B	
6584	[N II]	B	40.1	10.9	22.3	
6678	He I	1.6	1.4	2.9	3.3	
6717	[S II]	2.4	1.1	0.3	0.7	
6731	[S II]	5.4	2.6	0.8	1.4	

^a Explanation of symbols used: --- = not measurably present, NNS = nebular-night sky line blend, : = uncertain value, B = overexposed, f = masked by plate flaw.

^b Czyzak, Aller, and Kaler (1968).

Table 17
 N_e, T_e DATA FOR NGC 6543

$\lambda(\text{\AA})$	IDENT.	$f(\lambda)$	F-1	F-2	S
6717	[S II]	-.400	1.9	0.9	0.3
6731	[S II]	-.403	4.3	2.1	0.6
5755	[N II]	-.211	0.5	X	X
6548	[N II]	-.368	16.4	X	X
6584	[N II]	-.377	48.5*	X	X
		$r_1 =$	0.44	0.43	0.50
		log $r_2 =$	+2.11	X	X
		$N_e(r_1, r_2) \text{ in cm}^{-3} =$	39700	X	X
		$\overline{N_e(r_1)} \text{ in cm}^{-3} =$	X	45000	21600
		$T_e(r_1, r_2) \text{ in } ^\circ\text{K} =$	6900	X	X

* From $\lambda 6548$ Flux Value and Einstein Coefficients.

Fig. 17 - $I(\lambda, \theta)$ Contours for NGC 6826.

Table 18
F(λ) DATA FOR NGC 6826^a

$\lambda(\text{\AA})$	IDENT.	F	S	A	PHOTOELECTRIC DATA ^b
4686	He II	0.15	0.17	0.17	---
4713	He I	0.04	0.04	0.05	---
4861	H β	B	B	B	100
4922	He I	0.31	0.27	0.30	---
4959	[O III]	B	B	B	253
5007	[O III]	B	B	B	770
5048	He I	0.04	0.08	0.06	---
5517	[Cl III]	0.13	0.09	0.11	---
5538	[Cl III]	0.11	0.09	0.10	---
5577	[O I]NNS	0.39	0.48	0.39	---
5755	[N II]	0.14	0.06	0.06	---
5876	He I	8.97	21.37	13.90	13.9
6300	[O I]NNS	0.18	0.05	0.06	---
6310	[S III]	0.12	0.10	0.11	---
6364	[O I]NNS	0.10	---	---	---
6548	[N II]	6.02	0.84	0.91	---
6563	H α	B	B	B	287
6584	[N II]	26.18	2.23	4.87	---
6678	He I	1.19	1.56	1.23	4.7

Table 18 (continued)

$\lambda(\text{\AA})$	IDENT.	F	S	A	PHOTOELECTRIC DATA ^b
6717	[S II]	0.21	0.13	0.08	} 1.7
6731	[S II]	0.41	0.14	0.16	
7065	He I	1.47	1.26	0.99	---
7136	[Ar III]	4.76	3.47	3.40	5.7

^a Explanation of symbols used: --- = not measurably present,
 NNS = nebular-night sky line blend, : = uncertain value,
 B = overexposed, f = masked by plate flaw.

^b Czyzak, Aller, and Kaler (1971).

Table 19

 N_e , T_e DATA FOR NGC 6826

$\lambda(\text{\AA})$	IDENT.	$f(\lambda)$	F	S
6717	[S II]	-.400	0.13	0.08
6731	[S II]	-.403	0.26	0.09
5755	[N II]	-.211	0.11	0.05
6548	[N II]	-.368	4.01	0.56
6584	[N II]	-.377	17.26	1.47
5517	[Cl III]	-.158	0.11	0.08
5538	[Cl III]	-.163	0.09	0.08
		$r_1 =$	0.50	0.89
		log $r_2 =$	+2.29	+1.61
		$r_3 =$	X	1.12
		$N_e(r_1, r_2)$ in cm^{-3}	= 21100	3500
		$T_e(r_1, r_2)$ in $^{\circ}\text{K}$	= 6700	15000
		$N_e(r_2, r_3)$ in cm^{-3}	= X	2000
		$T_e(r_2, r_3)$ in cm^{-3}	= X	15200

Fig. 18 - $I(\lambda, \theta)$ Contours for NGC 3587.

Table 20
F(λ) DATA FOR NGC 3587^a

$\lambda(\text{\AA})$	IDENT.	A
4861	H β	100.0
4959	[O III]	449.3
5007	[O III]	B
5191	[Ar III]	1.2
5322	[Cl IV]	0.9:
5412	He II	1.4
5517	[Cl III]	1.6
5538	[Cl III]	2.1
5577	[O I]NNS	25.2
5755	[N II]	1.9
5876	He I	12.3
5914	He II	1.2:
5932	He II	2.0
5953	He II	2.2
5977	He II	1.8
6005	He II	1.3
6098		1.0:
6234	He II	3.7
6254		1.3
6286	S II	1.4
6300	[O I]NNS	11.6
6306	S II	3.7
6310	[S III]	3.4
6345		2.5
6347	Si II	1.9
6357	N II	3.8

Table 20 (continued)

$\lambda(\text{\AA})$	IDENT.	A
6364	[O I]NNS	3.7
6371	Si II	2.9
6423		2.8
6465		3.2
6498		3.5
6548	[N II]	30.5
6563	H α	463.6
6584	[N II]	126.4
6678	He I	6.9
6717	[S II]	20.1
6731	[S II]	16.1
6827	[Kr III]	6.8
6835		6.3
6865		8.9
6949		7.6
6979		4.5:
7006	[Ar V]	7.2
7065	He I	7.8:
7136	[Ar III]	9.4
7169	[Ar IV]	4.6:
7236	[Ar IV]	11.4
7263	[Ar IV]	10.7
7319	[O II]	5.4:
7331	[O II]	8.0:
7388		5.8:

^a Explanation of symbols used: --- = not measurably present, NNS = nebular-night sky line blend, : = uncertain value, B = overexposed, f = masked by plate flaw.

^b Aller and Czyzak (1971).

Table 21

 N_e, T_e DATA FOR NGC 3587

$\lambda(\text{\AA})$	IDENT.	$f(\lambda)$	A
6717	[S II]	-.400	17.5
6731	[S II]	-.403	14.0
5755	[N II]	-.211	1.8
6548	[N II]	-.368	26.9
6584	[N II]	-.377	111.0
5517	[Cl III]	-.158	1.5
5538	[Cl III]	-.163	2.0
		$r_1 =$	1.25
		log $r_2 =$	+1.88
		$r_3 =$	0.75
		$N_e(r_1, r_2)$ in $\text{cm}^{-3} =$	700
		$T_e(r_1, r_2)$ in $^{\circ}\text{K} =$	11200
		$N_e(r_2, r_3)$ in $\text{cm}^{-3} =$	8100
		$T_e(r_2, r_3)$ in $^{\circ}\text{K} =$	10400

Fig. 19 - $I(\lambda, \theta)$ Contours for IC 418.

Table 22
F(λ) DATA FOR IC 418^a

λ (Å)	IDENT.	A	PHOTOELECTRIC DATA ^b
4861	H β	B	100
4922	He I	1.6	---
4959	[O III]	B	41.7
5007	[O III]	B	153.2
5191	[Ar III]	1.2	---
5517	[Cl III]	0.6	---
5538	[Cl III]	0.9	---
5577	[O I]NNS	0.5	---
5669		0.3	---
5696	C III	0.4	---
5755	[N II]	4.9	20.7
5876	He I	B	25.6
6046		0.4	---
6098		0.3	---
6300	[O I]NNS	9.8	21.3
6310	[S III]	3.6	
6347	Si II	0.6	---
6364	[O I]NNS	3.7	12.4
6371	Si II	0.6	---
6548	[N II]	B	---
6563	H α	B	---
6584	[N II]	B	---
6678	He I	9.0	34.6
6717	[S II]	7.4	
6731	[S II]	18.2	

Table 22 (continued)

λ (Å)	IDENT.	A	PHOTOELECTRIC DATA ^b
6827	[Kr III]	0.7	---
6865		0.4	---
7006	[Ar V]	1.0	---
7065	He I	26.6	15.5
7136	[Ar III]	25.2	16.6
7236	[Ar IV]	2.6	---
7263	[Ar IV]	0.7	---
7281	He I	2.3	---
7319	[O II]	22.0	48.8
7331	[O II]	20.6	

^a Explanation of symbols used: --- = not measurably present, NNS = nebular-night sky line blend, : = uncertain value, B = overposed, f = masked by plate flaw.

^b Aller and Czyzak (1972).

Table 23
 N_e , T_e DATA FOR IC 418

$\lambda(\text{\AA})$	IDENT.	$f(\lambda)$	A
6717	[S II]	-.400	5.2
6731	[S II]	-.403	12.8
5517	[Cl III]	-.158	0.5
5538	[Cl III]	-.163	0.8
		$r_1 =$	0.41
		$r_3 =$	0.63
	$\overline{N_e(r_1)}$ in cm^{-3}	$=$	63000
	$\overline{N_e(r_3)}$ in cm^{-3}	$=$	12000

Chapter 4

CHARACTERISTICS OF THE FILAMENTARY STRUCTURE IN PLANETARY NEBULAE

Discussion of Observational Results

NGC 3242

This planetary is discussed first because the results obtained for it are fairly typical of objects observed with the spectrographic slit positioned as in setting I of Figure 1. Looking at Plate Ia, one notes that NGC 3242 consists of a bright inner region surrounded by a faint shell having brighter filamentary zones at its outer boundary. The F region studied centers on one of these rim features, while the S region occupies a section of the faint shell approximately the same distance from the central star as the F region.

The $I(\lambda, \theta)$ contours (Figure 10) for the nebular emission lines of singly ionized and neutral atoms show a prominent peak at the F position. The corresponding line fluxes (Table 4) are greater for the F region than the S region by a factor of 4 for [N II] $\lambda 6584$ and 3 for [O I] $\lambda 6300$ and [S II] $\lambda 6717$. Henceforth, such lines will be denoted as LIN (low ionization nebular) lines. The contours for low ionization auroral (LIA) lines are exemplified by [O I] $\lambda 5577$. No F peak is visible for the nebular component of this line, the

airglow component for this profile being obvious. Indeed, the F flux of this line is only 1.4 times greater than the S flux.

The contours for high ionization nebular (HIN) lines are considered next. The [Ar III] $\lambda 7136$ contour has a weak peak (compared to the strong LIN line peaks) at F and an F flux about equal to its S flux. The F and S fluxes are also approximately equal for the [Cl III] $\lambda 5517$ line, which shows a broad, weak peak in its contour, occurring closer to the S than to the F region. An example of a high ionization auroral (HIA) line is [S III] $\lambda 6310$. There is no F peak in its contour and little, if any, enhancement in the F over the S flux for this line.

The H β $\lambda 4861$ contour shows a peak at F which is less prominent than those of the LIN line contours. Of the He I line contours, a weak F peak is indicated in the $\lambda 5876$ line, but a weak S peak in the $\lambda 6678$ line. For both the $\lambda 5876$ line and the $\lambda 6678$ line, the F and S fluxes are about equal.

A further look at Table 4 shows the He II $\lambda 5412$ line to be present weakly in the S region, but absent in the F region, while the flux of He II $\lambda 6234$ is the same for both regions. The LIA [N II] $\lambda 5755$ line appears to be stronger in F than in S, although the low flux values make this inconclusive. Finally, the S fluxes of the [Ar IV] $\lambda 7236$ and $\lambda 7263$ lines, both HIA lines, are greater than their F fluxes.

Temperatures and densities will be discussed in terms of the criteria from which they are determined. For economy of presentation, the criterion for a T_e or N_e value will be indicated in

parentheses. This means that $T_e([O III])$ designates an electron temperature based on the lines of $[O III]$. In addition, the N_e and T_e values measured in this study are subscripted to indicate which region in the nebula they refer to. Thus, $N_{eF}(r_1, r_2)$ is the electron density of an F region derived from the r_1 ratio of $[S II]$ and the r_2 ratio of $[N II]$ (the only other criterion used in this study being the r_3 ratio of $[Cl III]$).

For NGC 3242, previous investigators have found $T_e([O III]) \approx 11,200^\circ K$ (Czyzak, Aller, Kaler and Faulkner 1966, Kaler 1966, Schmitter and Millis 1967, Kaler 1970) and $T_e(H) = 5700^\circ K$ (Kaler 1970). The temperatures listed in Table 5 are all somewhat higher than the above $T_e([O III])$ value, but perhaps still within the range of error for these values. $T_{eF}(r_1, r_2)$ is less than either $T_{eS}(r_1, r_2)$ or $T_{eS}(r_2, r_3)$, indicating that the filamentary region is cooler than the ambient gas even if the temperature scale should be shifted.

The published electron densities for NGC 3242 range from $N_e([O II]) = 1600 \text{ cm}^{-3}$ (Saraph and Seaton 1970) to $N_e([O II]) = 6300 \text{ cm}^{-3}$ (Czyzak, Aller, Kaler, and Faulkner 1966) and $N_e(H) = 8900 \text{ cm}^{-3}$ (Kaler 1970). The density values in Table 5 fall within this range, with $N_{eF}(r_1, r_2) = 5500 \text{ cm}^{-3}$ lying near the upper limit and $N_{eS}(r_1, r_2) = 2200 \text{ cm}^{-3}$ near the lower. This may mean that the $N_e(H)$ value and the higher $N_e([O II])$ value reflect emission from the brighter filamentary regions, whereas, the low $N_e([O II])$ value may be weighted mainly by emission from the inner ambient gas which

includes the bright interior section of the nebula. This is consistent with the suggestion of Czyzak et al. that filamentary effects are not important for this inner region and that much of the [O II] $\lambda 3727$ radiation may originate in the outer, more attenuated shell.

The filamentary region was found to be denser than the

ambient gas by $\frac{N_{eF}(r_1, r_2)}{N_{eS}(r_1, r_2)} = 2.50$ and cooler to the extent that

$\frac{T_{eF}(r_1, r_2)}{T_{eS}(r_1, r_2)} = 0.85$. Recalling equation (9) for the electron pressure, one finds from the above ratios that $\frac{P_{eF}}{P_{eS}} = 2.11$. One must bear in mind the possibility (discussed in Chapter 2) that $T_{eF}(r_1, r_2)$ may be an upper limit only. Lowering T_{eF} would lower P_{eF}/P_{eS} . Thus it is probably safe to conclude only that $\frac{P_{eF}}{P_{eS}} > 1$ for these regions of NGC 3242.

NGC 2392 I

As can be seen in Plate Ib, the bright inner zone of NGC 2392 is surrounded by an irregular filamentary shell. This shell is particularly prominent on direct photographs taken in the light of $H\alpha + [N II] \lambda\lambda 6548, 6584$ (Perek and Kohoutek 1967). The F region lies within the southern section of this shell, while the S region lies between the shell and the bright central region of the nebula.

The $I(\lambda, \theta)$ contours (Figure 11) for the LIN lines [N II] $\lambda 6584$ and [S II] $\lambda 6717$ show strong distinct peaks at F, while [O I] $\lambda 6300$, although not showing a distinct peak, has a maximum at this point.

The LIA lines [O I] $\lambda 5577$ and [N II] $\lambda 5755$ (no contour is available for the latter, see Table 6) behave as they do in NGC 3242, while the HIA line [S III] $\lambda 6310$ exhibits a weak broad peak at F. This same weak peaked appearance also holds for the H β and He I $\lambda 5876$ lines. The contour of the He II $\lambda 5412$ line shows its greatest strength at the S position, a behavior borne out by the F and S flux values for this line in Table 6. The photoelectric fluxes given in this table do not differ greatly from the F, S, and A values, but show no obvious correlation with any particular group of regional fluxes.

Kaler (1966, 1970) gives $T_e([O III]) = 17,300$ to $18,800^\circ K$ for this object. These values are much brighter than the T_{eF} and T_{eS} values in Table 7. The $T_e([O III])$ values probably reflect the conditions in the bright inner nebular regions. This region is prominent on direct photographs taken in the light of [O III] $\lambda\lambda 4959, 5007$, while the outer shell is less striking than on the H α + [N II] plates (both from Perek and Kohoutek 1967).

Kaler lists $N_e([O II]) = 8900 \text{ cm}^{-3}$ and $N_e(H) = 1400 \text{ cm}^{-3}$, whereas Saraph and Seaton (1970) give $N_e([O II]) = 6300 \text{ cm}^{-3}$. These $N_e([O II])$ values are higher than the N_{eF} value, while $N_e(H)$ is on the order of $N_{eS}(r_1, r_2)$. The ratios

$$\frac{N_{eF}(r_1, r_2)}{N_{eS}(r_1, r_2)} = 1.89 \text{ and } \frac{T_{eF}(r_1, r_2)}{T_{eS}(r_1, r_2)} = 0.73 \text{ again yield } \frac{P_{eF}}{P_{eS}} > 1.$$

NGC 2392 II

The positions of the F and S regions are shown in Plate Ib, while the $I(\lambda, \theta)$ contours are in Figure 12, the $F(\lambda)$ data in Table 8, and the T_e and N_e data in Table 9. The F vs S behavior of the $I(\lambda, \theta)$ and the $F(\lambda)$ data are similar to that of NGC 2392 I, except that [O I] $\lambda 6300$ now shows a definite peak at F. The only addition is the appearance of contours for [N II] $\lambda 5755$ (LIA line), He I $\lambda 6678$, plus [A III] $\lambda 7136$ (HIN line), all having weak peaks near F.

Generally, the same comments made about the photoelectric fluxes and the N_e and T_e data of NGC 2392 I apply here. However, $T_{eS}(r_1, r_2)$ is higher for this area than for NGC 2392 I, matching closely the T_e ([O III]) values given previously. The ratio

$$\frac{N_{eF}(r_1)}{N_{eS}(r_1, r_2)} = 1.33 \text{ is somewhat lower than for NGC 2392 I.}$$

NGC 2440 I

Plate Ic shows the positions of the three F and the S features studied in this irregular nebula. The $I(\lambda, \theta)$ contours, the $F(\lambda)$ data, and the N_e and T_e data are given in Figure 13, Table 10, and Table 11, respectively. Multiple peaks are prominent in the LIN line ([O I] $\lambda 6300$, [N II] $\lambda 6584$, [S II] $\lambda 6717$) contours. One may also note in Table 10 that the S fluxes of He II $\lambda 5412$ and $\lambda 6234$ are substantially greater than the average of the three F fluxes for these lines. The same statement can be made for the NGC 2440 I photoelectric data as for that of NGC 2392 I.

No feature can be seen on the Curtis (1918) sketch (see Plate Ic) at the position of the F' peak seen in many of the $I(\lambda, \theta)$ profiles. F' appears on long exposure spectrograms of the red spectral region, while the sketch was done from photographs of shorter exposure (probably on blue plates). This means that additional nebular structure must exist in the southern section of NGC 2440 near F'.

Previous studies (Kaler 1966, Aller, Czyzak, and Kaler 1968, Kaler 1970, Saraph and Seaton 1970) gave $T_e([O III]) = 13,400^\circ K$, $T_e(H) = 7300^\circ K$, and an average nebular $N_e([O II]) = 2700 \text{ cm}^{-3}$ plus $N_e([O II]) = 600 \text{ cm}^{-3}$ for an outer section of the nebula. The $T_{eS}(r_1, r_2)$ value agrees quite closely with $T_e([O III])$, the $T_{eF}(r_1, r_2)$ values being substantially lower. The average nebular $N_e([O II])$ falls within the range of $N_{eF}(r_1, r_2)$ values found, while $N_{eS}(r_1, r_2)$ is close to the lower $N_e([O II])$ value. So it appears here as if the [O III] emission comes primarily from the ambient gas, and the [O II] emission arises from filamentary regions.

The $\frac{N_{eF}(r_1, r_2)}{N_{eS}(r_1, r_2)}$ and $\frac{T_{eF}(r_1, r_2)}{T_{eS}(r_1, r_2)}$ ratios show that $\frac{P_{eF}}{P_{eS}} > 1$ for all three filamentary regions.

NGC 2440 II

The $I(\lambda, \theta)$, $F(\lambda)$, and the T_e and N_e data can be found, respectively, in Figure 14, Table 12, and Table 13. The results are substantially the same as those for NGC 2440 I. The only noteworthy point is that the S region here has a slightly lower

electron temperature and a slightly higher electron density than does the S region of NGC 2440 I. This may simply reflect the fact that the latter is closer to the nebula's center than the former.

NGC 6720

The $I(\lambda, \theta)$, $F(\lambda)$, and N_e and T_e data are given in Figure 15, Table 14, and Table 15, respectively. The features are identified on the direct photograph in Plate Id. As before, the F peaks are prominent in the LIN lines and very weak in the He I $\lambda 5876$ line.

Kaler (1966) gives $N_e([O II]) = 740 \text{ cm}^{-3}$ and $N_e(H) = 760 \text{ cm}^{-3}$, both on the order of the $\overline{N_{eS}(r_1)}$ value. The $\frac{\overline{N_{eF}(r_1)}}{\overline{N_{eS1}(r_1)}}$ ratios are high, ranging from 20 to 55 for the three filamentary regions studied. The S2 region has a density too low to be accurately determined by the r_1 ratio of [S II].

NGC 6543

This planetary, along with NGC 6826 and NGC 3587, was observed with the spectrographic slit in setting II of Figure 1. This can be seen for each nebula in Plate Ie,f, and g. The NGC 6543 results are given by the $I(\lambda, \theta)$ contours in Figure 16, the $F(\lambda)$ data in Table 16, and the N_e and T_e data in Table 17. Strong F peaks occur for the LIN lines ([O I] $\lambda 6300$, [N II] $\lambda 6548$, [S II] $\lambda 6717$), and weaker F peaks appear in the [N II] $\lambda 5755$ (LIA line), [Cl III] $\lambda 5538$ (HIN line), and [S III] $\lambda 6310$ (HIA line) contours. No F peaks

are evident for either [O III] $\lambda 4959$ (HIN line) or the H I and He I lines. The contours of the latter four lines resemble the λ_3 line profile in Figure 3. The NGC 6543 line contours qualitatively resemble similar drawn profiles for NGC 6720 by Chopinet (1963).

Czyzak, Aller, and Kaler (1968) give $T_e([O III]) = 8200^\circ K$, $T_e([S III]) = 7900^\circ K$, $T_e([Ar III]) = 9200^\circ K$, and $N_e([O III]) = 5600 \text{ cm}^{-3}$. Ko (1967) gives $T_e(H) = 2900^\circ K$, whereas Kaler (1970) gives $T_e(H) = 3700^\circ K$. The N_{eF} and N_{eS} values in Table 17 are much higher than either $N_e([O II])$ or $N_e(H)$. However, while finding $N_e([O II]) = N_e(H) = 6000 \text{ cm}^{-3}$, Weedman (1968) gives an $N_e([S II]) = 15000 \text{ cm}^{-3}$, which is in the neighborhood of $\overline{N_{eS}(r_1)}$.

Also, the ratios $\frac{N_{eF1}(r_1, r_2)}{N_{eS}(r_1)} = 1.8$ and $\frac{N_{eF2}(r_1)}{N_{eS}(r_1)} = 2.1$ are

similar to those for NGC 3242 and NGC 2392 (I and II).

NGC 6826

Figure 17 plus Tables 18 and 19 provide the $I(\lambda, \theta)$ contours, the $F(\lambda)$ data, and the T_e , N_e data for this nebula. The same description used for the NGC 6543 results applies to those of NGC 6826, except that only one F region is present instead of two. The addition here of contours for He II $\lambda 4686$ and [Ar III] $\lambda 7136$ allows one to see that the $I(\lambda, \theta)$ behavior of these lines also resemble the λ_3 profile in Figure 3.

Saraph and Seaton (1970) and Czyzak, Aller, and Kaler (1971) give the values $T_e([O III]) = 10,300^\circ K$ and $N_e([O II]) = 2100 \text{ cm}^{-3}$

for this nebula. $T_{eF}(r_1, r_2)$ lies below and $T_{eS}(r_1, r_2) = T_{eS}(r_2, r_3)$ lies above $T_e([O III])$. $N_{eS}(r_2, r_3)$ is about equal to $N_e([O II])$, with $N_{eS}(r_1, r_2)$ being somewhat higher. $N_{eF}(r_1, r_2)$ is approximately 10 times the $N_e([O II])$ value. The ratios

$$\frac{T_{eF}(r_1, r_2)}{T_{eS}(r_1, r_2)} = 0.45 \text{ and } \frac{N_{eF}(r_1, r_2)}{N_{eS}(r_1, r_2)} = 6.03 \text{ again yield } \frac{P_{eF}}{P_{eS}} > 1.$$

NGC 3587

The $I(\lambda, \theta)$ contours, the $F(\lambda)$ data, and the N_e and T_e data can be found in Figure 18, Table 20, and Table 21, respectively. As shown in Plate Ig, the spectrograph slit fell entirely within the inner, high excitation region of this nebula. As a result, no filamentary structure is evident in any of the line contours, all of which appear like the λ_3 line profile in Figure 3.

Previous investigators (O'Dell 1966, Ko 1967, Schmitter and Millis 1967, Kaler 1970) found that $T_e([O III]) \approx 11,000^\circ K$, $T_e(H) = 9200^\circ K$, and $N_e([O II]) = 230 \text{ cm}^{-3}$ for NGC 3587. The $T_{eA}(r_1, r_2)$ and $T_{eA}(r_2, r_3)$ values agree quite well with $T_e([O III])$; $N_{eA}(r_1, r_2)$ is of the same order of magnitude as $N_e([O II])$. However, the $N_{eA}(r_2, r_3)$ value is substantially higher than the other N_e figures, perhaps indicating the presence of density stratification along the line of sight through the nebula.

IC 418

The $I(\lambda, \theta)$ contours in Figure 19 show the cross section of IC 418's ring to be relatively homogeneous. Only slight evidence for a weak peak near $\theta = 15''$ of arc can be detected. The $F(\lambda)$ data are listed in Table 22, the N_e and T_e data in Table 23. Kaler (1966, 1970) gives $T_e([O III]) = 11,000^\circ K$, $T_e(H) = 4800^\circ K$, $N_e([O II]) = 42,000 \text{ cm}^{-3}$, and $N_e(H) = 21,000 \text{ cm}^{-3}$. The latter two values may be compared to $N_{eA}(r_1, r_2) = 63,000 \text{ cm}^{-3}$ and $N_{eA}(r_2, r_3) = 12,000 \text{ cm}^{-3}$. Weedman (1968) gives $N_e([S II]) = 19,000 \text{ cm}^{-3}$, but this may be averaged over the entire nebula. Thus, evidence exists for density fluctuations within the ring, in spite of its homogeneous appearance.

Summary and Conclusions

An overall picture of the filamentary (F) regions in planetary nebulae may be drawn from the discussion in the preceding section of this chapter. The F region peaks in the $I(\lambda, \theta)$ contours are by far the most prominent for the LIN line profiles. This prominence is underscored by the large values of the F region LIN line fluxes compared to the fluxes in the same lines arising from the surrounding gas (S regions). The F fluxes are in general about five times greater than the S fluxes for the $[O I] \lambda\lambda 6300, 6364$ lines, the $[N II] \lambda\lambda 6548, 6584$ lines, and the $[S II] \lambda\lambda 6717, 6731$ lines.

The LIA line contours have much weaker F peaks. The $[N II] \lambda 5755$ line, on the average, has an F flux that is about

twice its S flux, a much lower enhancement than for the LIN lines. The [O I] $\lambda 5577$ line, strongly contaminated by airglow, usually shows equal F and S fluxes. The blending with the night sky emission masks the nebular behavior of this line, leaving the [N II] $\lambda 5755$ line the only reliable indicator of LIA line characteristics.

The HIN and HIA line profiles show only broad weak peaks at the F positions. The HIN line [Ar III] $\lambda 7136$ plus the HIA line [S III] $\lambda 6310$ produce F fluxes that are about one and one half times larger than their S fluxes. For the [Cl III] $\lambda\lambda 5517, 5538$ lines (another set of HIN transitions), the F fluxes are approximately equal to the S fluxes.

Two distinct types of H line contours occur. For the first six nebular areas discussed, the H contours resemble those of the LIA lines. These profiles show definite F peaks, but the peaks are much less pronounced than those in the LIN line contours. For NGC 6543 and NGC 3587, the H line resembles the λ_3 contour in Figure 3. The only modification to the λ_3 behavior are sharp intensity decreases that occur in the H contour of NGC 6543. These drop-offs start near the F points and coincide positionally with the decline in peak intensity for the LIN profiles.

The H line contour characteristics also apply to the He I line contours. The major difference is that the He I peaks in the contours of the first six nebulae discussed are weaker and more diffuse than those in the H line profiles. It should also be noted that He I line contours of NGC 6826 resemble the H and He I profiles of NGC 6543. The He II lines, on the other hand, are always stronger

at the S positions than at the F positions. In general, the He II S region fluxes are approximately twice the F region values.

One can conclude from the previous paragraphs that the filamentary regions studied show a predominance of singly ionized and neutral atoms, whose strongest emission comes from forbidden nebular transitions. In addition, the T_e and N_e data consistently indicate that the F regions are cooler and denser than the neighboring S regions. These two major points, coupled with the general agreement of the previously discussed results with the descriptions of probable line behavior in Chapter 2, demonstrate that these filaments exhibit the properties ascribed to them by Capriotti (1972a) and Van Blerkom and Arny (1972). Further, the positional correlation between the contours of the [O I] $\lambda 6300$ line and the nebular transition lines of [N II] and [S II] serves as additional evidence, along with the photographs of Capriotti, Cromwell, and Williams (1971), that the [O I] and [N II] emissions originate primarily in filaments rather than in an H^+ to H^0 transition zone.

Two major puzzles remain. One is that $\frac{P_{eF}}{P_{eS}} > 1$ in every case for which this datum was attainable (as discussed earlier in the chapter for NGC 3242, this may simply reflect a limitation in $T_{eF}(r_1, r_2)$). The other anomaly is the tendency for weak F peaks to appear in the contours of HIN and HIA lines ([Cl III] $\lambda\lambda 5517$ and 5538 , [S III] $\lambda 6310$, and [Ar III] $\lambda 7136$) and the He I lines. Capriotti (1972a) predicts that He should be neutral in the filaments (He^+ being required to produce the He I recombination lines).

Since Cl^+ , S^+ , and Ar^+ have ionization potentials approximately equal to or greater than that of He^0 , no appreciable amounts of Cl^{+2} , S^{+2} , or Ar^{+2} would be expected to exist in these regions. Perhaps the observed F peaks in these lines indicate a slight increase in the electron density of the ambient gas within a packet of filaments over the electron density in the neighboring S region.

Three additional points of emphasis remain to be discussed. The r_1 ratio of [S II] and the r_2 ratio of [N II] are useful N_e and T_e criteria for application to the F and S regions, since S^+ and N^+ appear to spatially coexist. The comparison with N_e and T_e values of other investigators indicates that these physical parameters are dependent upon the criterion used for their measurement. This is simply due to the fact that the emission from various atomic and ionic species reflects the conditions in the density sub-region in which they predominate. This is important to remember when comparing N_e and T_e values from observations that integrate over the entire nebula with those from observations of localized areas. The results of this study indicate that the [O II] emission reflects conditions in filamentary regions more strongly than conditions in the ambient gas, while the opposite appears to be true for the [O III] emission. These results are consistent with the predicted density behavior for the emission from [O III], [O II], [N II], and [S II] presented in Figure 8 of Daub (1963).

The presence of filamentary structure also has a bearing on the construction of model planetary nebula. A case in point is

IC 418. The N_e data for this object show that density fluctuations probably exist in its bright ring, even though this nebula is too distant for any structure to be resolvable. This is consistent with the findings of Buerger (1971). That investigation determined that an inhomogeneous model gave better agreement between predicted and observed line fluxes than did the homogeneous case. This was particularly true for the LIN lines included in this model.

Finally, a comment should be made concerning the relation between the photoelectric and photographic line fluxes for these nebulae. In all cases, the photoelectric line fluxes were of the same order of magnitude as those for the F, S, and A regions. However, the sets of photoelectric fluxes showed no obvious correlation to the line fluxes from any one region, either A, S, or F. The following excerpt from Minkowski (1968) best sums up the situation.

. . . Here is perhaps the moment to point out that the differences between photoelectric and photographic results do not necessarily demonstrate the superiority of the photoelectric method, but often are likely to show differences between observations that integrate over the whole nebula and localized observations with a slit spectrograph. Good photographic photometry is difficult, but not necessarily much inferior, and possibly the method of choice for detailed studies.

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