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**Spectrophotometry of Bowen resonance fluorescence lines in
three planetary nebulae**

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Rice University, 1992

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RICE UNIVERSITY

**Spectrophotometry of
Bowen Resonance Fluorescence Lines
in Three Planetary Nebulae**

by

Christopher O. Miller

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

Master of Science

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Abstract

Spectrophotometry of Bowen Resonance Fluorescence Lines in Three Planetary Nebulae

by

Christopher O. Miller

This thesis studies the Bowen resonance fluorescence mechanism of OIII in three planetary nebulae: NGC 6210, 7027, and 7662. It utilizes the best spectra to date of this phenomena in the wavelength range of 3100 Å–3850 Å. The data are presented in the form of flux ratios relative to the strong 3444.1 Å line and compared to expectations based on current theory. Harrington’s theoretical predictions which take into account the additional enhancement of some of the Bowen resonance fluorescence lines due to pumping of next higher energy level, OIII 2p3d $^3P_1^0$, show agreement with NGC 7027 and 7662; however, predictions by Neufeld agree poorly for all three planetary nebulae studied. Enhancement by charge exchange reactions is quite evident in NGC 6210. Finally, the HeII 3203 Å line is used to determine efficiencies of 0.57 and 0.48 for NGC 7027 and 7662 respectively, only slightly higher than Kallman and McCray’s prediction of 0.42; while NGC 6210 yielded an impossible value of 1.37.

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And, since I know she'll be reading this: I owe it all to my mother.

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1 INTRODUCTION

1.1 The Basic Bowen Resonance Fluorescence Mechanism

It is best to begin this thesis by clearly explaining the Bowen resonance fluorescence [BRF] mechanism. It will be helpful to refer to Figure 1 during this discussion. BRF occurs due to the coincidental near match of the HeII Ly α line at 303.78 Å and the OIII $2p^2\ ^3P_2 - 2p3d\ ^3P_2^0$ line at 303.80 Å¹. Both of these lines result from electron recombinations to the ground state of their atoms. The atoms in the ground state then become the targets of the 303.78 Å and 303.80 Å photons. The 303.78 Å photons are readily absorbed by HeII in the ground state. They then spontaneously emit that same photon in the permitted transition back to the ground state. The same thing occurs for the 303.80 Å photons and OIII. One can visualize this repeated absorption and emission as photons that are randomly walking through the nebula; where each turn in their path is an absorption/emission encounter with an atom in its ground state. The 303.78 Å and 303.80 Å photons are *resonant* line photons.

There are several mechanisms that can destroy these resonant photons. In the case of the BRF mechanism, some of the HeII Ly α photons on the red wing of the 303.78 Å line will encounter ground state OIII ions and be absorbed in a $2p^2\ ^3P_2 - 2p3d\ ^3P_2^0$ transition. The thermal Doppler broadening of emission lines works both ways, so naturally some of the OIII photons are absorbed by HeII; but, since there is over 100 times more helium in the nebula than oxygen, many

¹Throughout this thesis I will adopt the usual atomic quantum notation. The energy levels are described by the quantum numbers of the pair of valance electrons in an OIII ion, $nl\ n'l\ ^{2S+1}L_J^\circ$. The quantum numbers are defined as follows: n —principal, l —orbital, S —total spin, L —total orbital, J —total angular. The “ $^\circ$ ” denotes odd parity; if the summed l are odd, the term has odd parity.

FIGURE 1: Grotrian Diagram of OIII
Showing the Bowen Resonance Fluorescence Lines

Wavelengths are Angstroms in air except for $\lambda < 3000\text{\AA}$ which are given in vacuum. The thick line represents the $2p3d\ ^3P_2$ energy level which is pumped by the O1 photons. The $2p3d\ ^3P_0$ level is not populated by the HeII Ly α photons so cascade lines originating from it are not shown. The velocity displacement of some OIII lines from the center of HeII Ly α is shown in km s⁻¹.

more oxygen lines are enhanced at the expense of the HeII Ly α than the other way around. The OIII $2p^2\ ^3P_2 - 2p3d\ ^3P_2^0$ line is enhanced by *fluorescence* with HeII Ly α .

These resonance fluoresced OIII $2p^2\ ^3P_2 - 2p3d\ ^3P_2^0$ line photons are themselves resonant, but occasionally they cascade down to the ground state via $2p3p - 2p3d\ ^3P_2^0$ and $2p3s\ ^3P_J^0 - 2p3p$ transitions. These transitions fall in the 2800Å–3800Å range. The HeII Ly α pumping of the $2p3d\ ^3P_2$ OIII state is ultimately responsible for the observed brightness of the 2800Å–3800Å OIII lines in several planetary nebulae [PNs], and it was *Bowen* (1934, 1935) who first pointed out that fluorescence with the resonant line of HeII Ly α was the cause. Hence, this phenomenon bears his name: the Bowen resonance fluorescence mechanism.

1.2 Historical Background

The study of PNs began well before Bowen’s explanation for the OIII lines. Stuart R. Pottasch’s (1983) book, Planetary Nebulae A Study of Late Stages of Stellar Evolution, gives a historical review that it worth summarizing here. In the latter part of the eighteenth century, astronomers noticed cloud like formations in the heavens. The latin word for ‘clouds’ is ‘nebulae’, which is what all these objects were called; though we know now that many of the objects were galaxies or star clusters, not what we would call nebulae today. The search was on, and soon over two thousand ‘nebulae’ were found. In 1785, Herschel referred to the class of nebulae that appeared as round greenish disks as ‘planetary nebulae’, due to their similarity in appearance to the planet Uranus he had discovered in 1781.

At that time, a debate was raging as to whether nebulae were composed of stars or some luminous fluid. In 1790 Herschel noticed a star at the center of a PN (NGC 1514) and deduced correctly that a PN was a star surrounded by luminous gas. In 1864, Huggins took the first spectrum of a PN (NGC 6543), and in 1865 he found emission lines that did not correspond to any previously identified elemental lines. These mystery lines were ascribed to a new element called nebulium. The search for nebulium in the laboratory and a theoretical explanation for its emission properties was fruitless. Eventually, the search for an explanation turned toward H, He, C, N, and O—five elements that were known to exist in nebulae. Finally, in 1927, Bowen (1928) realized that Huggins’s nebulium lines were actually OIII forbidden lines. Soon, all the unidentified lines in nebular spectra turned out to be due to forbidden lines, arising from an electronic transition between a metastable state and the ground state.

1.3 Recent Work on the Bowen Resonance Fluorescence Mechanism

Along with the question of what ions produced the nebular emission line spectra, there was also the desire to explain their fluxes using atomic theory. The problem this thesis addresses is the excessive brightness of some permitted OIII lines. As was the case in the early study of PNs spectra, observations raised questions that would guide later theory. Improved technology has resulted in better observational data, revealing new physical processes. Observations of the BRF OIII lines indicate that they are due to more than just pumping by the HeII Ly α photons.

It was Bowen (1934, 1935) that first put forth the idea that resonance fluorescence with HeII Ly α was the cause of the enhanced OIII emission in PNs. Since then, Saraph and Seaton (1980) [SS] and Kastner and Bhatia (1990) [KB] have derived expected intensity ratios of OIII lines which follow the excitation of OIII 2p3d $^3P_2^0$. The BRF lines in various astronomical objects represent some of the best ‘laboratories’ for the study of resonance line transfer. Kallman and McCray (1980) compare model static PNs with real PNs and compact X-ray sources; Bhatia and Kastner (1988) compare calculations for both optically thin and thick conditions to the PN NGC 6720. As more and more PNs are observed, a characteristic efficiency is emerging: about one half of the HeII Ly α photons are being converted to OIII photons in PNs (O’Dell and Opal 1989).

So far, I have addressed only the most basic BRF mechanism—the HeII Ly α pumping of OIII 2p3d $^3P_2^0$. Figure 1 also illustrates the pumping of OIII 2p3d $^3P_1^0$. The bottom five transitions lines of Figure 1 show (in addition to their wavelengths in Angstroms) the amount their line centers are Doppler shifted from the pumping HeII Ly α line. It is clear from the figure that the main absorbing line is at 303.799 Å; this is called the O1 line. The 303.693 Å line can also be important; it is called the O3 line. The other three have Doppler shifts which place them so far out on the wings of the HeII Ly α line that they are unimportant to the study of the BRF mechanism.

The expected intensity ratios of OIII lines following the excitation of OIII 2p3d $^3P_1^0$ have been derived by Deguchi (1985, erratum 1986). Figure 1 shows that all of the lines out of the 2p3d $^3P_{1,2}^0$ states are pumped either by O3 or O1. The relative

intensities of these $2p3p - 2p3d \ ^3P_{1,2}^0$ lines are then a measure of the relative pumping of the $2p3d \ ^3P_1^0$ and $^3P_2^0$ states and hence, the relative pumping rates of O3 and O1 respectively. Neufeld (1990) has calculated the ratio of the pumping rate of O3 to the pumping rate of O1 for the case of a uniform, static slab. He shows in his figures 22 and 23 the dependence of the pumping ratio on HeII column density and the ratio of the OIII to HeII densities. Harrington (1972) also made similar calculations for the case of an expanding shell PN. The ratio of the $2p3p - 2p3d$, O1 and O3 pumped lines, called the primary cascades by SS, are good diagnostics for any region showing BRF. The $2p3s - 2p3p$ lines, called the secondary cascades by SS, are also affected by O3 pumping, but are not as useful for studying the O3 to O1 pumping ratio.

There is another phenomenon that can greatly affect the intensities of some of the secondary cascade lines: the charge exchange [CE] reaction

The collision of neutral hydrogen with OIV can result in OIV taking the neutral hydrogen's electron. When this happens, the electron will often populate one of the $2p3p$ states of OIII, enhancing the secondary BRF lines. This possibility was first addressed by Dalgarno and Sternberg (1982). Sternberg, Dalgarno, and Roueff (1988) have calculated the expected intensity ratios of some of the secondary OIII lines arising from the charge transfer event of Equation 1. Their calculations made use of Roueff and Dalgarno's (1988) cross sections obtained from quantum mechanical scattering theory.

These three different methods of creating OIII lines: BRF by O1, BRF by O3,

and CE, will preferentially populate specific energy levels of the OIII ion. The O1 and O3 lines each cause primary cascades unique to the pumping line (see columns two and three of Table 2). The BRF primary cascades preferentially populate 3S_1 , 3P_J , and 3D_J , in that order; while CE preferentially populates 3D_J , 3S_1 , and 3P_J . Thus, the relative importance of these three different mechanisms in creating the bright OIII lines can be sorted out. That is a major aim of this thesis.

1.4 Bowen Resonance Fluorescence in Astrophysical Objects

So far I have mainly considered the existence of BRF in PNs. While that is the study of this thesis, the reader should not believe that PNs hold a monopoly on the BRF process. Since the main ingredient for BRF is the coexistence of HeII Ly α photons and OIII ions, one would expect the OIII BRF lines to be found in many ionized sources. Schachter's PhD thesis studied the BRF mechanism in several astrophysical objects and resulted in the following papers: Schachter, Filippenko, and Kahn (1989) study the Sco X-1 x-ray source; Schachter, Filippenko, and Kahn (1990) study active galactic nuclei; Schachter *et al.* (1991) and Wallerstein *et al.* (1991) study close binaries. These are some rather exotic objects; this thesis studies the BRF in PNs, and since they are comparatively well understood objects, we can use them to increase our understanding of the BRF mechanism more easily.

2 OBSERVATIONS

All the observations were carried out on the McDonald 2.7 m telescope, using the Large Cassegrain Spectrograph and the 140 mm f/1.4 quartz Bowen block Schmidt camera. The TI 800×800 $15 \mu\text{m pixel}^{-1}$ CCD detector was operated in the backside-illuminated mode, with the width of the entrance slit corresponding to roughly two CCD pixels. Soaking the backside of the chip in dry NO gas results in a fifty fold increases in sensitivity at $3000 \text{ \AA}$. This is the same CCD chip used by O'Dell *et al.* (1991) and the process of improving the ultraviolet sensitivity was first detailed there.

Specific data for the eighteen spectra used in this study are given in Table 1. It should be noted that the standard star absolute flux data we used are modifications of the original Stone (1977) absolute flux data. As Bohlin (1986) pointed out, the Stone values for the standard stars BD +28°4211 and BD +33°2642 at $\lambda < 3300 \text{ \AA}$ seem too low when compared with IUE measurements. When the IUE and Stone flux data for the two standard stars are plotted together, it becomes clear that the data are well represented by a blackbody except for the decrease in flux from $3200 \text{ \AA}$ – $3300 \text{ \AA}$ as given by the Stone data. Since nothing else in these star's spectra corroborates this drop in flux, we normalized the Stone absolute flux data to a blackbody and used the blackbody points for $\lambda < 3400 \text{ \AA}$ instead of the Stone data. This is the same modification of the Stone data used previously by O'Dell and Opal (1989).

TABLE 1
OBSERVING AND DATA REDUCTION INFORMATION
ON PN SPECTRA USED IN THIS STUDY

Night	Exposure Times (min.)	Airmass	Data Rows Averaged	Slit Size on Sky	Position Angle	Range in λ ($\text{\AA}$)	Size of Data Pixel
NGC 6210							
2 June 1990	30	1.42	18	1" x 140"	90°	3000–3625	0.89 $\text{\AA}$ x 1.28"
	30	1.26					
2 June 1990	30	1.02	18	1" x 140"	90°	3325–4000	0.89 $\text{\AA}$ x 1.28"
	30	1.02					
NGC 7027							
26 July 1989	30	1.03	21	2" x 80"	62°	3000–4250	1.7 $\text{\AA}$ x 1.28"
	30	1.02					
30 July 1989	20	1.08	21	2" x 80"	62°	3150–3550	0.89 $\text{\AA}$ x 1.28"
	20	1.12					
NGC 7662							
26 July 1989	30	1.05	30	2" x 80"	62°	3000–3575	1.7 $\text{\AA}$ x 1.28"
	30	1.03					
	30	1.02					
29 July 1989	30	1.13	30	2" x 80"	62°	3000–3575	0.89 $\text{\AA}$ x 1.28"
	30	1.08					
	30	1.04					
	30	1.03					
	30	1.02					
30 July 1989	30	1.02	30	2" x 80"	62°	3150–3850	0.89 $\text{\AA}$ x 1.28"
	30	1.03					

In all cases the entire planetary nebulae was contained within the length of the slit.

3 REDUCTION OF DATA

For the most part, standard IRAF² (Image Reduction and Analysis Facility) techniques were used to reduce the raw data to usable form. The dark noise level was determined from an unilluminated portion of each spectrum and subtracted out. A dome flat was uniformly illuminated by a quartz continuum lamp and several exposures taken each night. These flat-field calibration spectra were used to determine differences in the pixel to pixel sensitivity of the CCD chip and this effect was corrected for in the PNs and calibration spectra. Hg and Ar lamps were used for wavelength calibration. Any further defects in the PNs spectra—cosmic ray hits, CCD defects too gross to be corrected for by the flat-field techniques, were removed ‘by hand’. Correction for the affects of atmospheric extinction were made using the Tegler and O’Dell (1987) extinction curve, which we believe to be an improvement over the IRAF McDonald extinction curve. The flux calibration, which converted CCD counts to $\text{ergs cm}^{-2} \text{s}^{-1} \text{\AA}^{-1}$, used the standard stars BD +28°4211 and BD +33°2642 and their revised Stone absolute flux values as mentioned in Section 2.

Further data reduction combined the eighteen PNs separate spectra into our final seven—one for each PN’s spectral set-up. The images for each particular PN/spectral set-up were averaged together. The averaged two-dimensional images were line averaged along the spatial dimension to create the final one-dimensional spectra. The final one-dimensional spectra represent the average of several expo-

²IRAF is distributed by the National Optical Astronomy Observatories, which is operated by the Association of Universities for Research in Astronomy, Inc., under cooperative agreement with the National Science Foundation.

tures and the spatial average along the entrance slit of the entire PN.

These final seven images were then modified to make the process of emission line flux measuring as simple and accurate as possible. Their wavelengths were corrected to laboratory values. The sum of the atomic and stellar continuum was fit by a series of smooth curves and subtracted, leaving a pure emission line spectrum (see Figure 2).

Several IRAF flux measuring techniques were used, depending on the strength of the line and if it required deblending with any nearby line. Each line was measured using different integrating and Gaussian fitting techniques yielding several different values for the line's flux. The values from the different techniques were then weighted, or deleted entirely, depending on factors such as agreement with the predicted line center and reasonable full-width-at-half-max's of 5 Å for the low dispersion spectra and 2 Å for the high dispersion spectra.

The accuracy of our final flux values was determined mainly by the accuracy with which the nebular continuum was determined. For wavelengths longer than 3646 Å, the Balmer confluence made finding the continuum level between crowded H lines uncertain. At 3421 Å there is an ill-defined HeI discontinuity. Shortward of 3400 Å there was a problem with contamination due to atmospheric ozone absorption. The best discussion on ozone contamination to date is by Schachter (1991). It is difficult to determine the difference between the nebular continuum between two emission features and an ozone absorption feature which may be present. Using the table of ozone absorption coefficients from Valley (1965) and the ozone absorption features present in our standard stars we were able to identify the atmospheric ozone absorption features. The uncertainty in the flux was determined by measuring the

All lines are Bowen OIII lines unless stated otherwise. Three lines are off scale. Note the ozone absorption bands around 3200Å.

emission lines above what we considered to be a highest possible nebular continuum and a lowest possible nebular continuum; it ranges from $\pm 10\%$ to over $\pm 30\%$.

The effect the ozone absorption has on the calibration of our relative absolute fluxes is not completely known. The amount of ozone absorption will change from night to night, with air mass, and with observatory location. Ozone absorption was surely present when Stone observed the standard stars and calibrated their absolute flux values. The absolute flux tables used for this paper were in bins of ~ 50 Å. Since we used blackbody values for the standard stars for $\lambda < 3400$ Å, the wavelength region where the ozone absorption is a problem, our absolute flux standard values should not have been affected. However, contamination by ozone absorption is definitely something to be aware of when observing in this spectral region—3000 Å–3400 Å.

The final fluxes for the Bowen lines, HeI 3187, and HeII 3203 are given in Table 2. The flux values are relative to the strong 3444 Å line and have been corrected for interstellar extinction using Seaton’s (1979) extinction curve and Kaler’s (1976) extinction values for the PNs.

4 COMPARISON WITH THEORY

4.1 Explanation of Table 2

In this section we shall quantitatively consider the role of all of the processes contributing to the production of the observed BRF OIII emission lines. As explained in Section 1.3, this includes BRF excitation by both the O1 and O3 lines, and the lines produced by charge exchange [CE] reactions. Table 2 gives the dereddened

TABLE 2

EXPECTED AND REDDENING CORRECTED FLUX RATIOS OF BOWEN AND RELATED LINES

$\lambda(\text{\AA})$	Theoretical Ratios			NGC 6210			NGC 7027			NGC 7662		
	O1	O3	CE	Expected	Observed		Expected	Observed		Expected	Observed	
				O1+O3	O1+O3+CE	This study	O1+O3	O1+O3+CE	This study	O1+O3	O1+O3+CE	This study
3405.7		0.124		0.0384	0.0384	0.069:	0.0112	0.0112	0.013:	0.0149	0.0149	0.024:
3415.3		0.092		0.0285	0.0285	0.102:	0.0083	0.0083	0.024:	0.0110	0.0110	0.024:
3428.7	0.336			0.383	0.383	0.31	0.350	0.350	...	0.354	0.354	0.18
3430.6		0.154		1.000	1.000	1.00	1.000	1.000	1.00	1.000	1.000	1.00
3444.1	1.000											
3121.7		1.000		0.310	0.310	0.31	0.090	0.090	0.09	0.120	0.120	0.12
3132.9	3.615			3.615	3.615	3.23	3.615	3.615	3.06	3.615	3.615	3.12
3299.4	0.0996	0.0275	0.0583	0.108	0.122	0.23	0.102	0.106	0.12	0.103	0.106	0.13
3312.3	0.297	0.082	0.1792	0.323	0.366	0.41	0.305	0.316	0.32	0.307	0.315	0.34
3340.7	0.493	0.136	0.300	0.536	0.607	0.62	0.506	0.524	0.47	0.510	0.523	0.48
$^3S_1 \rightarrow ^3P^0$	0.891	0.246	0.538	0.987	1.094	1.26	0.913	0.946	0.91	0.920	0.944	0.95
3754.7	0.0177	0.024	0.542	0.0251	0.1540	0.22:	0.0199	0.0533	0.042:	0.0206	0.0452	0.048:
3757.2	0.000875	0.0060	0.242	0.135	0.430	0.43	0.133	0.210	0.21	0.134	0.190	0.19
3759.9	0.132		1.000									
3774.0	0.000652	0.0045	0.1833	0.0020	0.0456	0.032:	0.0011	0.0124	0.017:	0.0012	0.0095	0.008:
3791.3	0.00585	0.008	0.1771	0.0083	0.0504	0.059	0.0066	0.0175	0.014	0.0068	0.0149	0.018
3811.0	0.0000435	0.00030	0.1216	0.0001	0.0290	0.010:	0.0001	0.0076	...	0.0001	0.0056	...
3187.7				HeI (3187.74 \AA) $1s4p\ ^3P^0 \rightarrow 1s2s\ ^3S_1$ and HeII (3203.10 \AA) $5^2F \rightarrow 3^2D$								
3203.1				2.189					0.086			0.094
				0.313					0.716			0.864

All ratios are $I(\lambda)/I(3444.10)$ except for the third and fourth columns which are $I(\lambda)/I(3121.71)$ and $I(\lambda)/I(3759.87)$ respectively. Typical uncertainties in the reddening corrected ratios are $\pm 10\%$ except for those followed by a : which are $\pm 30\%$ at best. The $\pm 10\%$ uncertainty for the 3791.3 \AA line is an underestimate due to its low flux.

flux ratios for each of the PNs. The rows are grouped in multiplets of OIII, except for the last two rows which are helium emission lines. The first column gives the wavelength. The second, third, and fourth columns are the relative intensities of the emission lines due to O1 pumping (SS), O3 pumping (Delguchi 1985, 1986), and CE (Dalgarno and Sternberg 1982 and Sternberg, Dalgarno, and Rouff 1988) respectively. It should be noted that SS have an error in their Table 4 column eight: the relative intensity for the 3810.68 Å line should read 0.000012 instead of 0.00012. Also, Delguchi's (1986) erratum has an error in that the relative intensity of I(3299.4 Å) should be 0.0275 and not 0.275. In order to add the effects of these three different processes to get a final expected flux ratio, O1 + O3 + CE, one must first scale the importance of these mechanisms using observational data. Our procedure is as follows.

The ratio of intensities of the Bowen lines with the 3444.1 Å line due to the pumping by the O1 line is the standard to which we scaled the other line producing mechanisms. Since the 3132.7 Å line is only produced by the O3 pumping mechanism it was used to scale the other lines: the factor, which when multiplied by the theoretical relative intensity of I(3132.7 Å) (1.000) yielded the observed dereddened flux ratio for I(3132.7 Å), was multiplied by all the theoretical ratios due to O3 pumping in column 3. These scaled values were then added to the theoretical ratios due to O1 pumping in column 2 and the sum became the O1 + O3 columns for each PN (columns 5, 8, and 11). To add the effects of CE, the 3757.2 and 3759.9 Å lines were used. The 3759.9 Å line is not enhanced by O3 line pumping, so any observed excess in the observed I(3759.9 Å) was assumed to be due to CE enhancement. Observationally, the 3759.9 Å line was blended with the 3757.2 Å line, so they had

to be treated together. The sum of the theoretical ratios for these two CE produced lines is 1.242. The excess between the observed and expected O1 + O3 pumped flux ratios of I(3757.2 + 3759.9 Å) was assumed to be due entirely to CE enhancement. The factor, that when multiplied by 1.242 and added to the expected O1 + O3 produced I(3757.2 + 3759.9 Å) ratio yielded the observed I(3757.2 + 3759.9 Å) ratio, was multiplied by the CE produced relative intensities in column 4 and added to the expected O1 + O3 produced flux ratios for each PN to create the final expected flux ratios due to the O1 + O3 + CE mechanisms (columns 6, 9, 12).

It is the observed dereddened flux ratios (columns 7, 10, 13) that we will use to discuss the relative importance of O1, O3, and CE. Of the six sets of transitions, two primary and two secondary sets have observed dereddened fluxes sufficiently well measured to disentangle the roles of O1, O3, and CE. The primary cascades are used to determine the amount of O3 pumping; the secondary cascades are used to determine the amount of CE enhancement. The two remaining sets of transitions are unusable due to atmospheric extinction.

4.2 Primary Cascades and O1 and O3 Pumping

For the rest of this section, we will proceed to examine each observed dereddened line in turn, making statements about the importance of O1, O3, and CE or whether the observed dereddened fluxes ratios are adequately explained by current theory at all.

The primary cascades are not affected by CE so their observed dereddened flux ratios should arise only from O1 and O3 pumping of the $2p3d\ ^3P_{2,1}^0$ states. The SS

expected flux ratios for O1 pumping are given in column two of Table 2; the Deguchi (1985, erratum 1986) expected flux ratios for O3 pumping are in column three of Table 2 (both with the previously mentioned corrections). KB did not calculate the expected flux ratios for O1 pumping for as many lines as SS, so the KB results are not included in Table 2, but they will be addressed in the text.

The $2p3p\ ^3P_J - 2p3d\ ^3P_{2,1}^0$ lines result from primary cascades falling in the 3400 Å–3450 Å range. All but the strong 3444.1 Å line are badly blended. This is the reason the 3444.1 Å line is used to scale the others. The HeI discontinuity mentioned in Section 3 also falls in this region at 3421 Å. The 3405.7 Å and 3415.3 Å lines both arise from O3 pumping. Unfortunately, both are blended with OIV recombination lines: the 3405.7 Å line is blended with a 3403.6 Å line and the 3415.3 Å line is blended with a 3411.8 Å line. This makes them unsuitable for determining the amount of O3 pumping in our PNs. The 3428.7 Å and 3430.6 Å lines are blended with each other; and, in NGC 7027 and 7662 they are further blended with a 3425.9 Å [NeV] line. SS expect an intensity for $I(3428.7\ \text{Å})$ of 0.336 and KB expect 0.164 (both relative to $I(3444.1\ \text{Å})$). It is possible to determine the amount of flux in the 3428.7/3430.6 Å blend due only to 3428.7 Å since we can determine how much O3 pumping is occurring using the 3121.7 and 3132.9 Å lines (explained in Section 4.1). In NGC 6210, the $I(3430.6\ \text{Å})$ contribution to the blended relative flux is only 0.048 (0.154×0.31) so the dereddened relative flux of $I(3428.7\ \text{Å})$ for NGC 6210 is 0.26 ($0.31 - 0.048$). Typical uncertainties in the observed values are $\pm 10\%$ so NGC 6210 does not agree with either SS or KB, but falls between their values. In NGC 7027, the blending with the [NeV] made a study of this line pair impossible. In NGC 7662, the [NeV] is not as intense and deblending of the 3428.7/3430.6 Å

pair and [NeV] was attempted. The observed dereddened flux ratio of I(3430.6 Å) is 0.018 (0.154×0.18) so the flux ratio of I(3428.7 Å) is 0.16 ($0.18 - 0.018$). This is consistent with KB, though the accuracy of the deblending is uncertain. As mentioned earlier, the 3121.7 Å line is best for determining the amount of O3 pumping, so the 3430.6 Å line is not considered further. The 3444.1 Å line is strong and free of blending problems; its uncertainty is actually closer to $\pm 5\%$ than 10% .

The $2p3p\ ^3S_1 - 2p3d\ ^3P_{2,1}^0$ lines result from primary cascades falling at 3121.7 and 3132.9 Å. These appeared as good unblended features in our spectra. The 3121.7 Å line has the distinction of being the only line resulting from a primary cascade pumped by O3 that lies in the atmospheric window i.e. has a wavelength above ~ 3100 Å, and has no blending problems. As was mentioned in Section 4.1, it is used to scale the Deguchi (1985, 1986) expected flux ratios due to O3 pumping. This is why the expected flux ratios due to O1 + O3 + CE exactly match observations for the 3121.7 Å line (this line experiences no CE enhancement). Since the 3132.9 and 3444.1 Å lines arise only from BRF via O1 pumping, we expect the observed dereddened flux ratio of these two lines to be the same for all three PNs. The average observed dereddened flux ratio of I(3132.9 Å) is 3.13 ± 0.17 . SS predict this value to be 3.615, while KB predict 4.451. The most likely reason for this discrepancy is that the 3121.7 Å line falls right on top of a terrestrial ozone absorption feature. The similarity in the 3121 Å and 3132 Å line's quantum parameters and their similar wavelengths make them the best candidate for examining O3 pumping. The ratio of the observed dereddened flux ratios, I(3121.7 Å) to I(3132.9 Å), is very nearly equal to the ratio of the rate of O3 to O1 line absorption by OIII. For NGC 6210 this ratio is 0.10; for NGC 7027 it is 0.03; for NGC 7662 it is 0.04.

The $2p3p\ ^3D_J - 2p3d\ ^3P_{2,1}^0$ lines come from primary cascades falling in the 2800–2850 Å range. They are outside the atmospheric window and are not studied in this thesis.

4.3 Secondary Cascades and Charge Exchange enhancement

The secondary cascades arise from the $2p3p$ triplet S, P, and D energy states that are populated by the primary cascades. The CE reaction of OIV with neutral hydrogen can also populate these levels. The expected relative fluxes for lines produced by CE have been calculated by Dalgarno and Sternberg (1982) and Sternberg, Dalgarno, and Rouff (1988) and are in column four of Table 2. Their paper only uses two significant digits, so there is some round-off error present in our Table 2. They gave no relative intensities for I(3791.3 Å) or I(3811 Å), so we used the branching probabilities of SS to determine their expected flux ratios. The intensities of emission lines out of the same energy level depend mostly on their branching ratios (for our temperatures and densities); since the expected flux ratios for all the other lines from the $2p3p\ ^3D_J$ multiplet were given, they can be used to scale I(3791.3 Å) and I(3811 Å).

The $2p3s\ ^3P_J^0 - 2p3p\ ^3P_J$ lines result from secondary cascades falling in the 3025–3060 Å range. They fall just inside the atmospheric window and only the strongest lines were detectable. The signal-to-noise was so bad that nothing quantitative can be said about them and they are not addressed any further in this thesis. Luckily the effect of CE on these lines is expected to be negligible.

The $2p3s\ ^3P_J^0 - 2p3p\ ^3S_1$ lines result from secondary cascades falling in the 3300–3350 Å range. They are well measured except for minor blending of the 3340.7 Å line with 3345.9 Å [NeV]. Once the amount of CE enhancement of these lines has been determined using the 3757.2 and 3759.0 Å lines, (discussed in Section 4.1) the effect can be added to O1 and O3 pumping. The expected O1 + O3 + CE flux ratios can then be compared with the observed dereddened flux ratios. CE enhancement does not affect the $2p3s\ ^3P_J^0 - 2p3p\ ^3S_1$ lines as much as the $2p3s\ ^3P_J^0 - 2p3p\ ^3D_J$ lines. If we add the relative flux of all three of the $2p3s\ ^3P_J^0 - 2p3p\ ^3S_1$ lines (this is shown in Table 2) the affect of CE enhancement on this multiplet becomes clearer. For NGC 6210, the O1 + O3 + CE expected flux ratio is 1.094; the observed dereddened flux ratio is 1.26 ± 0.13 . This slight discrepancy is possibly explainable by too low a measurement of the 3757.2 and 3759.0 Å lines in NGC 6210. For NGC 7027 and NGC 7662 the expected flux ratios are 0.946 and 0.944 respectively; the observed dereddened flux ratios are 0.91 and 0.95. The agreement is excellent.

The $2p3s\ ^3P_J^0 - 2p3p\ ^3D_J$ lines result from secondary cascades falling in the 3750–3810 Å range. Many of these lines were badly blended in our spectra and have uncertainties of about $\pm 30\%$. For I(3754.7 Å), all three PNs expectations agree with observations within their $\pm 30\%$ uncertainty, with NGC 7662 showing very good agreement. The 3757.2 and 3759.0 Å lines are blended enough in our spectra that they are best treated together. The 3759.0 Å line is the most affected by CE enhancement; so, as was mentioned in Section 4.1, this blend is used to scale the effects of CE. This is why their observed dereddened flux ratio shows exact agreement with the O1 + O3 + CE expected flux ratio. The 3774.0 Å line was blended with 3770.6 Å Balmer H11. For NGC 6210, the observed value is lower

than expected. The actual observed flux ratio for this PN was 0.01–0.06. This range contains the expected flux ratio though, again, there is an implication that the I(3757.2 and 3759.0 Å) flux ratio may be underestimated in NGC 6210. For NGC 7027 and 7662 there is agreement within the observational uncertainties. The 3791.3 Å line did not have severe blending problems, but its low flux makes adoption of $\pm 20\%$ uncertainty prudent. With the adoption of $\pm 20\%$ uncertainty in the observed dereddened flux, all three PNs show agreement with predictions. The 3811.0 Å line is expected to be quite weak. Furthermore, there is a HeII line at 3813.5 Å. The 3811.0 Å line was possibly identified in NGC 6210; but in NGC 7027 and 7662 a positive identification could not be made.

4.4 He Lines

In order to determine the efficiency of the BRF in removing HeII Ly α photons, and to explore other aspects of BRF in these PNs, the observed dereddened flux ratio of two helium lines were also measured. Neither of these lines had blending problems and their uncertainties are in fact better than the typical $\pm 10\%$.

5 DISCUSSION

5.1 O1 and O3 Pumping

In this section we will compare the relative pumping rate of O3 to O1 obtained using the observational data with the models of Neufeld (1990) and Harrington (1972). But first, it will be instructive to explain where in the PNs the BRF process is

occurring.

As explained in Section 1.1, the necessary condition for BRF is the coexistence of HeII Ly α photons and OIII in the ground state. The ionization potential of He⁺ is 54.4 eV; the ionization potential of O⁺² is 54.9 eV. This means that HeII and OIII are competing for the same ionizing photons in the nebulae, and hence, the HeII/HeIII and OIII/OIV ionization boundaries are the same. In the HeIII zone of the nebulae, the following photo-ionization/recombination equilibrium reaction takes place

The HeII Ly α line can be formed during the recombination process; and thereafter, the HeII Ly α line photons will resonantly scatter off ground state HeII ions. In the OIV zone of the nebulae, the following photo-ionization/recombination equilibrium reaction takes place

Since we've already established the fact that the HeIII and OIV zones exist in the same region of the nebula, one can see that HeII Ly α photons in the HeIII zone can be absorbed by residual ground state OIII ions in the same zone. Spatial plots of an OI pumped BRF line and a HeII line show both emission lines coming from the same region of the nebulae; unfortunately, inadequate spatial resolution precludes this from being considered conclusive evidence.

We are now in a position to compare Neufeld's (1990) and Harrington's (1972) models with theory. Neufeld's (1990) model consisted of a uniform static slab composed mainly of HeII with a HeII Ly α source at the center. The destruction of

FIGURE 3: Neufeld's Figure 23: Pumping Ratio as a function of $N(\text{O}^{+2})/N(\text{He}^+)$

Ratio of the pumping rate in the O3 line to that in O1, as a function of $N(\text{O}^{+2})/N(\text{He}^+)$. The pumping rates are averaged over a slab with a central source of $\text{He}^+\text{Ly}\alpha$ radiation, and absorption by O^{+2} is assumed to be the only loss process. Each curve is labeled with the quantity $\log_{10}[N(\text{He}^+)/\text{cm}^{-2}]$.

$\text{HeII Ly}\alpha$ occurred only due to O1 and O3 pumping of OIII. Except for the location of the $\text{HeII Ly}\alpha$ photons, Neufeld's model is quite similar to PNs conditions described in the previous paragraph. Harrington's (1972) model is one of an expanding shell PN.

Neufeld's (1990) figure 23 (our Figure 3) shows the dependence of the pumping ratio [PR] of O3 to O1 on the HeII column density and on the ratio of OIII to HeII ion densities. The PR is shown to be a maximum of $1/3$ for large HeII column density $N(\text{He}^+)$ i.e. optical depth, and small ratio of ion densities $N(\text{O}^{+2})/N(\text{He}^+)$. From $1/3$, the PR decreases as $N(\text{He}^+)$ decreases and as $N(\text{O}^{+2})/N(\text{He}^+)$ increases. Qualitatively, this figure shows that for large $N(\text{He}^+)$, the $\text{HeII Ly}\alpha$ line will be broadened enough that an equal number of $\text{HeII Ly}\alpha$ photons are pumping both

the O1 and O3 lines. The pumping rate is then simply the ratio of their stimulated absorption Einstein coefficients. As $N(\text{He}^+)$ decreases, the HeII Ly α line width begins to shrink, leaving the O3 line to absorb fewer photons in the HeII Ly α line wing. As the $N(\text{O}^{+2})/N(\text{He}^+)$ ratio increases, the pumping ratio decreases because the O1 line is able to absorb most of the HeII Ly α photons; the O1 is effectively acting as a photon sink that keeps the HeII Ly α line from broadening enough to pump the O3 line.

Figure 23 makes use of Neufeld's equation 5.25 which has the nebular gas temperature and the ion density ratio, $N(\text{O}^{+2})/N(\text{He}^+)$ as parameters. If our explanation for where BRF occurs is correct, then the following two photo-ionization/recombination equilibrium equations are valid (Osterbrock, 1989).

$$N(\text{He}^+) \int_{\nu_T}^{\infty} \frac{4\pi J_\nu}{h\nu} a_\nu(\text{He}^+) d\nu = N(\text{He}^{+2}) N_e \alpha_B(\text{He}^+, T) \quad (4)$$

$$N(\text{O}^{+2}) \int_{\nu_T}^{\infty} \frac{4\pi J_\nu}{h\nu} a_\nu(\text{O}^{+2}) d\nu = N(\text{O}^{+3}) N_e \alpha_G(\text{O}^{+2}, T) \quad (5)$$

Where J_ν is the mean intensity of the radiation (which is almost entirely just the radiation emitted by the central star), ν_T are the threshold ionization frequencies, a_ν are the photoionization cross sections, and α_B and α_G are the recombination coefficients. These two equations yield a simple relation for the ratio of ion densities in the BRF emitting region.

$$\frac{N(\text{O}^{+2})}{N(\text{He}^+)} = \frac{N(\text{O})}{N(\text{He})} \frac{\alpha_G(\text{O}^{+2}, T)}{\alpha_B(\text{He}^+, T)} \frac{a_T(\text{He}^+)}{a_T(\text{O}^{+2})} \quad (6)$$

The substitution of $N(\text{O})/N(\text{He})$ for $N(\text{O}^{+3})/N(\text{He}^{+2})$ has been made since in the HeIII/OIV zone of nebulae, most of the helium and oxygen are in the doubly and triply ionized states respectively, HeII and OIII being only trace species. The approximation of $a_T(\text{He}^+)/a_T(\text{O}^{+2})$ for the ratio of the integrals is accurate to about

10% for these PNs³ and works in part due to the very similar ionization potentials of He⁺ and O⁺—54.4 and 54.9 eV respectively. Numerical values for the above equation are found in Osterbrock (1989) Tables 2.7–2.9, 2.11, and 5.13. Assuming a typical PN gas temperature of 10,000 K, we get $N(\text{O}^{+2})/N(\text{He}^{+}) = 0.0179$. Neufeld’s Equation 5.25 is adequate for smaller values of $N(\text{O}^{+2})/N(\text{He}^{+})$, but in this case, an extra term needs to be added. Neufeld’s equation 5.25 then becomes

$$\text{PR} = \frac{\epsilon_{03}(1 + \sqrt{6}\epsilon_{01}|\sigma_{01}|)}{\epsilon_{01}(1 + \sqrt{6}\epsilon_{03}|\sigma_{03}|)} \quad (7)$$

where $\epsilon_{01} = 3 \times 10^{-3}N(\text{O}^{+2})/N(\text{He}^{+})$, $\epsilon_{03} = 10^{-3}N(\text{O}^{+2})/N(\text{He}^{+})$, $\sigma_{01} = 4250$, and $\sigma_{03} = 5.9 \times 10^5$, all values again being for the characteristic temperature of 10,000 K. Using this equation, we obtain a PR of 0.0193. Compare this value with the PR’s for NGC 6210, 7027, and 7662 determined in Section 4.2 of 0.10, 0.03, and 0.04 respectively. Our PR are all significantly larger than Neufeld’s revised equation predicts. By using line intensities of other PNs found in Kaler (1976), PR’s for other PNs were calculated; all of them had PR’s greater than the predicted value. Harrington’s (1972) model predicts a PR of 0.031 when the PN electron temperature is set at 11,000 K.

The agreement with Harrington’s prediction is reassuring, but it remains to be explained why the prediction using the modified Neufeld equation is too low. The PR before adding the extra $\sqrt{6}\epsilon_{01}|\sigma_{01}|$ term was 1.56 times lower, so it’s possible that further refinement of the equation will result in better agreement. It is also possible that HeII Ly α migration into the HeII/OIII region may be significant and/or that HeII Ly α photons resonant scattering in the HeII/OIII region are producing a

³The 10% accuracy of this approximation is based on the comparison of the ratio of the threshold cross sections, a_T , with the actual ratio of the integrals calculated using Mathematica. A black body spectrum was used for J_ν and Osterbrock’s (1989) Equation 2.31 was used for a_ν .

significant amount of BRF emission lines. In cases of an extremely large PR, like NGC 6210, it is possible that bulk motion within the PN may be responsible for a blue shifted HeII Ly α component which could O3 pump OIII. A current belief is that in some PNs, fast stellar winds impact into the slower moving, higher density, previously ejected shells. This morphology might be able to produce the necessary blue shifted HeII Ly α lines.

5.2 Charge Exchange Enhancement

It is quite obvious, especially in NGC 6210, that CE enhancement of the OIII BRF lines can be a significant factor in some of the secondary cascade line fluxes. In some cases, CE increases the line flux an order of magnitude over expectations based on O1 and O3 pumping alone. But why do some PNs show more CE enhancement than others?

If we assume that CE is occurring in the HeIII/OIV zone, where BRF lines are created, then the CE to BRF ratio of emissivities [j] is

$$\frac{j(\text{CE})}{j(\text{BRF})} \propto \frac{N(\text{H}^0)}{N_e} \frac{N(\text{O}^{+3})}{N(\text{He}^{+2})} \quad (8)$$

In the HeIII/OIV zone, the $N(\text{O}^{+3})/N(\text{He}^{+2})$ ratio is the same as $N(\text{total oxygen})/N(\text{total helium})$ —the ratio of their atomic abundance in the PN, neglecting other trace ionization species. Therefore, since atomic abundances are fairly constant from one PN to another, it is the different $N(\text{H}^0)/N_e$ ratios from one PN to another that result in different $j(\text{CE})/j(\text{BRF})$ ratios for different PN. So PNs with a higher ionization degree for hydrogen should have a smaller $j(\text{CE})/j(\text{BRF})$ ratio. This implies that PNs with cooler stars will have a higher $j(\text{CE})/j(\text{BRF})$ ratio; they

have higher a $N(H^0)/N_e$ ratio, so the $N(H^0)$ fuels more CE reactions. In the case of NGC 6210, NGC 7027, and NGC 7662, the central star temperatures are about 50,000 K, 300,000 K, and 100,000 K respectively (Pottasch, 1983), with the cooler NGC 6210 showing around four times more CE enhancement than NGC 7027 or NGC 7662.

A measure of the degree of ionization is the $I(\text{HeI})/I(\text{HeII})$ ratio. Our results combined with those of Likkell and Aller (1986) show a slight correlation were PNs with larger $I(\text{HeI})/I(\text{HeII})$ have larger $j(\text{CE})/j(\text{BRF})$ ratios. It is hard to be more specific than this, since the fact that PNs with high $I(\text{HeI})$ often have low $I(\text{HeII})$ which will tend to lower $j(\text{BRF})$ regardless of the effects of CE.

5.3 Bowen Resonance Fluorescence Efficiency

The efficiency $[R]$ of the BRF process is defined as the fraction of BRF lines which arise following the creation of a HeII Ly α line. O'Dell and Opal (1989) use the 3203.1 Å HeII and 3132.9 Å OIII lines to determine R . The 3132.9 Å OIII line is an excellent choice as it is the brightest BRF line and a primary cascade line: it is well measured observationally, and well understood quantum mechanically. The 3203 Å HeII line is near the 3132.9 Å line and is a cascade that precedes the HeII Ly α line: it reduces possible inaccuracies due to systematic effects in data reduction and is a good diagnostic for the unobserved HeII Ly α line at 303.80 Å (40.9 eV). The efficiency equation is

$$R = \frac{I(\text{OIII}, 3132.9)}{f(3132.9/\text{BRF}) \times h\nu_{3132.9}} \times \frac{f(3203.1/\text{HeII Ly}\alpha) \times h\nu_{3203.1}}{I(\text{HeII}, 3203.1)} \quad (9)$$

$f(3132.9/\text{BRF})$ is the fraction of photons in the 3132.9 Å OIII line as compared to the total number of primary OI BRF photons; it is the probability for emission of the 3132.9 Å line following the excitation of OIII $2p3p\ ^3P_2^0$. $f(3203.1/\text{HeII Ly}\alpha)$ is the fraction of photons in the 3203 Å HeII line as compared to the number of HeII Ly α generated by the central ionizing star; it is the ratio of the effective recombination coefficients of HeII 3203.1 and HeII Ly α . If one makes use of emissivities from Osterbrock (1989, p. 81), branching ratios from SS, and assumes a PN gas temperature of 10,000 K, the equation becomes

$$R = 0.133 \frac{I(\text{OIII}, 3132.9)}{I(\text{HeII}, 3203.1)} \quad (10)$$

This equation gives efficiencies for NGC 6210, 7027, and 7662 of 1.37, 0.57 and 0.48 respectively.

Kallman and McCray (1980) calculated an expected R of 0.42 for static PNs. This does not agree with NGC 6210 at all; clearly something else is at work in this nebula since it is quite impossible to convert more than 100% of the HeII Ly α photons! NGC 7027 and 7662 are both fairly close to the expected value, but 0.42 still lies below the typical $\pm 10\%$ uncertainty of the PN values. There is a strong terrestrial ozone absorption feature at 3200 Å that may be lowering the observed $I(\text{HeII}, 3203.1)$ flux by a significant amount. While this could explain the R for NGC 7027 and 7662, it's not likely to be the whole reason for the absurdly large R for NGC 6210. Unless there is some other method besides BRF that might increase $I(\text{OIII}, 3132.9)$, the high R for the three PNs must be due to a low $I(\text{HeII}, 3203.1)$. Possibly some of the 3203.1 Å photons are being destroyed after leaving the BRF zone; or the amount of HeII Ly α photons based on $I(\text{HeII}, 3203.1)$ has been underestimated. Dust in a shell outside the BRF region of a PN would be more effective at lowering the observed

I(HeII Ly α) resonant line flux, but would be no more likely to remove 3203.1 Å HeII photons than 3132.9 Å OIII photons, which is what we actually measured. If the PN electron temperature was higher than 10,000 K, then the same I(HeII,3203.1) would correspond to less HeII Ly α and our efficiency, R, would be an underestimate. But, for NGC 6210's efficiency to agree with expectation, or even drop below 1.00, we would need to assume a nebular gas temperature over 20,000 K which is twice the value given in Pottasch 1984 (p. 296).

The BRF mechanism is an interesting process. Once it is better understood, it will become a valuable probe of PNs and other astrophysical objects. The amount of BRF and the presence of O3 lines are directly affected by the shape of the HeII Ly α line, which is dependent on the thermal and turbulent properties within the nebulae. The amount of CE could be an indicator of a nebulae's degree of ionization. Of course it may be much more complicated than this, but this thesis has shown that, with the exception of a few peculiarities, good observation are in agreement with recent theory. Further refinement of the atomic theory combined with good observations should some day be able to turn the study of resonance line transfer from a research topic into an astrophysical diagnostic tool.

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