RevMexAA (Serie de Conferencias), **10**, 38–41 (2001)

A BI–COMPONENT SPECTRAL ANALYSIS OF 4 PLANETARY NEBULAE

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RESUMEN

Presentamos un análisis de cuatro nebulosas planetarias que muestran líneas de emisión desdobladas en distintas componentes espectrales por efecto Doppler. Las componentes roja y azul se han analizado por separado para obtener el enrojecimiento, la temperatura electrónica, la densidad electrónica y las abundacias iónicas y totales para cada objeto en dos regiones de cada nebulosa. Posteriormente comparamos las condiciones físicas obtenidas con cada componente (roja y azul) buscando variaciones que podrían indicar inhomogeneidades reales.

Encontramos una variación de 1600K en T_e[O III] para la región central de NGC 6309, con posibles variaciones en n_e[O II], c(Hβ) y N/H entre las dos componentes. También se observa una variación de 1500K en T_e[O III] entre componentes para la región central de NGC 6751. Aún tomando en cuenta estas variaciones al calcular los cocientes O^{2+}/H^+, persisten discrepancias entre los valores derivados de líneas de recombinación vs. líneas colisionales.

Finalmente notamos que las velocidades de expansión tanto para las líneas de recombinación como para líneas colisionales de O^{2+} son las mismas, indicando así que estas líneas están trazando el mismo volumen de emisión.

ABSTRACT

Presented here is the analysis of four planetary nebulae which show well–resolved Doppler splitting of their emission lines into distinct spectral components. The red, (**R**), and blue, (**B**), components of the spectral lines have been separately analyzed to obtain the reddening, the electron temperature, the electron density, and the ionic and total abundances for each object within two areas of each nebula along the line of sight. The derived physical conditions for the **R** and **B** components were then compared to see if any variations occurred along the line of sight within these objects, indicating the presence of physical imhomogeneities along the line of sight.

For the central spectrum of NGC 6309, a variation of 1600K in T_e[O III] is found, along with suggested variations in n_e[O II], c(Hβ) and N/H between the **R** and **B** components. For the central position of NGC 6751, T_e[O III] varies by 1500K between the **R** and **B** components. However, despite taking these T_e variations found for NGC 6309 and NGC 6751 into account when calculating O^{2+}/H^+ ratios, discrepancies still exist between ratios derived from the recombination vs. the collisional lines.

It is finally noted that the expansion velocities for both the collisional and recombination lines of O^{2+} are the same, indicating that the same volume of emission is traced by these lines.

Key Words: **ISM: ABUNDANCES — PLANETARY NEBULAE: GENERAL**

The Seventh Texas-México Conference on Astrophysics: Flows, Blows and Glows (Austin, Texas, 6-8 April 2000)
Editors: William H. Lee and Silvia Torres-Peimbert

1. INTRODUCTION

We have observed four planetary nebulae (PN; NGC 4361, NGC 6309, NGC 6751, and NGC 6905) with the echelle spectrograph and 2.3–m telescope at the Observatorio Astronómico Nacional at San Pedro Mártir, Ensenada B. C., México. These PN all show clear Doppler splitting of their emission lines into two components, hereafter denoted as the red–shifted (**R**) and blue–shifted (**B**) components. We have performed separate nebular analysis of the **R** and **B** components for each nebula. We were interested in determining whether there were variations in the physical conditions (i.e. reddening, electron temperature, electron density, chemical abundances) from component to component, and hence along the line of sight. If such variations were to be found, would they be large enough to account for the problem of discrepancies between the chemical abundances determined from recombination lines and those determined from collisionally excited lines? Objects with these discrepancies include NGC 6210 (Kingsburgh et al. 1997), NGC 6543 (Kingsburgh, López & Peimbert 1996), and NGC 6572 (Peimbert, Storey & Torres–Peimbert 1993).

For 3 objects, NGC 6309, NGC 6751, and NGC 6905, spectra were taken at both a position near or on the central star, and at a second position a few degrees offset from the central star. For NGC 4361 only a central position spectrum was taken.

2. ANALYSIS AND RESULTS

The spectra were reduced and analyzed in the standard manner. c(Hβ) was derived using the Balmer decrement and the spectra were dereddened according to Seaton (1979). Electron temperatures, densities and abundances were calculated using the program EQUIB (Adams, Howarth, Liu, University College, London). Quoted errors on derived quantities are based on measurement errors propagated through calculations. Table 1 presents c(Hβ), n_e[O II], T_e[O III] and T_e[N II]. Individual objects are discussed below. Table 2 presents total abundances derived for the **R** and **B** components. The T_e[O III] variations found for NGC 6309 and NGC 6751 (discussed below) were taken into account when deriving the overall abundances. The final O/H abundances for the **R** and **B** components of these objects are, however, the same within errors. The only significant abundance discrepancy found is the N/H abundance for NGC 6309.

A few weak recombination lines were present in our spectra. Table 3 presents the recombination and forbidden line O^{++}/H^{+} ratios along with the derived t^2 values. A full presentation of this work is in progress (Armour & Kingsburgh 2001, in preparation).

3. DISCUSSION OF INDIVIDUAL OBJECTS

3.1. *NGC 4361*

This is a highly ionized object with T_e[O III]=19600±1400 K. We find a possible discrepancy in the He/H ratio, derived between the **R** component, where He/H=0.094±0.006, and the **B** component, where He/H=0.113±0.005.

3.2. *NGC 6309*

We find a T_e variation of 1600 K between the **B** and **R** components. In the **R** component, T_e[O III]=11700 ±300 K, while in the **B** component, T_e[O III]=13300±200 K. There is also a possible variation in c(Hβ) between the two components of the central spectrum with the **B** component having c(Hβ)=0.80±0.05 and the **R** component having c(Hβ)=0.95 ±0.05, which may suggest the presence of internal dust within this object. There is also a possible variation in n_e[O II] with the **B** component having log(n_e[O II])=3.0:: and the **R** component having log(n_e[O II])=4.2±0.5. However, the uncertainty on the $\lambda\lambda$3726,29 fluxes from the **B** component is very high. There is also a possible N–deficiency in **B** component (see Table 2). From our observations, this object appears to have a hotter, less dense **B** component, and a cooler, more dense **R** component.

TABLE 1

REDDENING, ELECTRON TEMPERATURES AND ELECTRON DENSITIES

Object	Comp	c(Hβ)	n_e[O II]	T_e[O III]	T_e[N II]
NGC 4361	R	0.20 ± 0.05	...	19400 ±1400[a]	...
	B	0.20 ± 0.05	...	...	...
NGC 6309	R	0.80 ± 0.05	4.2 ± 0.5	11700 ± 200	9800 ± 200
(central)	B	0.80 ± 0.05	3.0::	13300 ± 200	...
NGC 6309 (offset)		0.70 ± 0.05	3.5 ± 0.1	10400 ± 100	–
NGC 6751	R	0.70 ± 0.05	3.3 ± 0.1	11000 ± 300	8400 ± 300
(central)	B	0.70 ± 0.05	3.2 ± 0.1	12500 ± 200	8800 ± 300
NGC 6751	R	0.70 ± 0.05	3.2 ± 0.2	11000 ± 400	8200 ± 200
(offset)	B	0.70 ± 0.05	3.4 ± 0.2	10100 ± 400	8600 ± 300
NGC 6905	R	0.30 ± 0.05	2.9 ± 0.2	13000 ± 300	...
(central)	B	0.30 ± 0.05	3.4 ± 0.3	12100 ± 300	...
NGC 6905	R	0.30 ± 0.05	2.9 ± 0.1	12600 ± 200	8200[a]± 500
(offset)	B	0.30 ± 0.05	3.2 ± 0.2	12400 ± 300	...

[a] Total values :: - very uncertain errors of 50% or higher

3.3. *NGC 6751*

This object a shows a T_e variation in the central spectrum of 1500 K with the **R** component having T_e[O III]=11000±300 K and the **B** component having T_e[O III]=12500±200 K. There is also a possible T_e variation in the offset spectrum of 900 K with **R** having T_e[O III]=11000±300 K and **B** having T_e[O III]=10100±200 K. It is interesting to note that the T_e in the **B** component varies between central and offset spectra, while the T_e the **R** component does not.

3.4. *NGC 6905*

This object has equal c(Hβ), T_e, n_e and abundances between the **R** and **B** components, within errors.

4. CONCLUSIONS

Variations in physical conditions (including T_e) have been found between the **R** and **B** components, and hence along the line of sight. These T_e variations however, were *not* large enough to explain the discrepancies found between O^{2+} abundances derived from recombination vs. collisionally lines (Table 3). One explanation for this discrepancy is that the lines originate from different regions of the nebulae. The collisional lines would preferentially arise in hotter areas, while recombination lines arise in areas of lower temperature. However, we have found that the derived expansion velocities do not support this idea. In NGC 6309 the collisional lines of O^{2+} yield $2V_{exp}$=63.6±5.0km/s, while the recombination line (λ4340) yields $2V_{exp}$=59.5±5.0km/s. In NGC 6905 the collisionally excited lines of O^{2+} yield $2V_{exp}$=90.4±5.0km/s, while the recombination line (λ4168) yields $2V_{exp}$=86.3±5.0km/s. In both objects the velocities for the collisionally excited lines and the recombination lines are the same within error, indicating that these lines arise from the same volume within the nebula. This suggests that temperature variations on a macroscopic scale are not the cause of the abundance discrepancies, although variations on a microscopic scale cannot be ruled out.

TABLE 2

TOTAL ABUNDANCES[a]

Object		He/H	O/H (10^{-4})	N/H (10^{-4})	N/O	Ne/H (10^{-4})	Ar/H (10^{-6})
NGC 4361	**R**	0.113±0.006	2.26±0.56	...	...	0.30±.15a	2.19±1.10
	B	0.094±0.005	2.31±0.57	...	...	...	2.32±1.16
NGC 6309	**R**	0.110±0.005	4.70±0.94	1.47±.38	0.31	0.79±0.20	2.25±1.15
(central)	**B**	0.106±0.005	5.90±1.18	0.24±0.6	0.04	1.34±0.38	4.60±2.30
(offset)		...	5.69±1.14	2.20±0.55	0.39	1.35±0.36	0.91±0.45
NGC 6751	**R**	0.109±0.005	5.47±1.12	1.58±0.38	0.29	1.16±0.30	...
(central)	**B**	0.109±0.005	4.12±0.83	1.01±0.25	0.25	1.05±0.29	...
NGC 6751	**R**	0.107±0.005	4.97±0.98	1.77±0.47	0.33	1.23±0.33	...
(offset)	**B**	0.115±0.006	6.15±1.21	2.03±0.51	0.36	1.31±0.35	0.16±0.40
NGC 6905	**R**	0.107±0.007	4.30±0.86	0.51±0.14	0.12	0.98±0.25	1.37±0.67
(central)	**B**	0.098±0.005	6.21±1.24	0.74±0.18	0.12	1.45±0.37	1.92±0.96
NGC 6905	**R**	0.097±0.005	4.60±0.94	0.64±0.16	0.14	1.08±0.27	1.35±0.67
(offset)	**B**	0.098±0.005	5.32±1.08	0.75±0.19	0.14	1.37±0.38	1.34±0.62
Solar[b]		0.085±0.009	6.76±1.14	0.83±0.12	0.12	1.20±0.16	2.51±0.37

[a] Total abundance for **R** & **B** [b] Solar abundances taken from Grevesse & Sauval 1998

TABLE 3

RECOMBINATION VERSUS FORBIDDEN IONIC ABUNDANCES

Object	Ion	Recombination	Forbidden	t^2
NGC 6309(**R**)(central)	O^{++}	1.64 ±0.83(x10^{-3})	2.19±0.41 (x10^{-4})	0.065
NGC 6751(Tot.)(offset)[a]	O^{++}	1.78 ±0.36(x10^{-3})	3.87±0.77 (x10^{-4})	0.06
NGC 6905(**R**)(offset)	O^{++}	4.20:: (x10^{-4})	1.72 ± 0.34 (x10^{-4})	0.05
NGC 6905(**B**)(offset)	O^{++}	7.02::(x10^{-4})	1.46 ± 0.30 (x10^{-4})	0.065

[a]Total value taken as an average of **B** and **R** components. The O^{++} abundance for NGC 6309 is from O II λ4650; O^{++} abundance for NGC 6751 is from O II λ4640; O^{++} abundances for NGC 6905 are from O II λ4168.

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