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SPECTROSCOPIC DETERMINATION OF ELECTRON TEMPERATURE AND ELECTRON DENSITY OF PLANETARY NEBULAE

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ABSTRACT

The electron temperature of 16 Planetary Nebulae were determined by means of $[OIII]$ *forbidden line intensities. The forbidden* $[OIII]$ *lines* $\lambda 5007, \lambda 4959$ *and* $\lambda 4363$ *were identified from the spectra obtained from the "astrosurf" planetary nebulae archives. The observed intensities for these lines were corrected for interstellar reddening. The calculated electron temperatures ( ) of our sample spectra range were between* $9000 \lesssim T_e \lesssim 24000\ K$ *while the ratio* $I(5007)/I(4959)$ *was in* ~ 2.6 *and* ~ 3.5*. The intensity rations of* $[SII]$ *forbidden lines,* $\lambda\ 6716$ *and* $\lambda\ 6731$*, were also determined for these planetary nebulae in order to evaluate the electron densities. A mathematical model was constructed to estimate the electron temperature of a Planetary nebula from* $[OIII]$ *line ratios.*

KEYWORDS: *Electron temperature, Electron densities, Interstellar reddening*

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1. INTRODUCTION

A planetary Nebula (PN) is a typically small, faint nebulae, created during the final stages of an Asymptotic Giant Branch (AGB) star whose birth mass was comparable to the Sun. This aging star undergoes a series of bursts in luminosity called thermal pulses which eject shell of material into space and divests itself completely of its outer layers. These outer layers of gas expand into space, forming a gas envelope around the core of the star. The remaining central core is known as white dwarf which no longer supports itself by fusion reactions in its center. The gravitational forces due to the material in the outer part of the core that push the inner parts, make the central core more heated up. The temperature of this central core, white dwarf, generally sometimes exceeds ~200,000K and it emits UV radiations which are energetic enough to ionize and excite the expanding outer gas envelope. These gases then glow and emit visible light through the fluorescence. Therefore, a PN is a very low density cloud of ionized gas around its central star.

Under the low density condition, the PN spectra were identified as being collisionally excited "forbidden" lines of the ionized and neutral forms of common elements such as oxygen, nitrogen, and carbon.

The recombination lines which occurred due to the cascade of the electron down the ground state can also be identified in PN spectra. The recombination lines include the H, He and many very-faint lines of other elements.

PN can be recognized by their emission line spectra and the absence of continuum. Emission lines & stellar spectrums and Spectroscopic methods can be used to extract those spectrums with the help of reference spectrums of telescopes using image analysis facility software. In order to analyze the spectrums, we used IRAF V2.16 (Image Reduction and Analysis Facility), developed by National Optical Astronomy Observatories (NOAO) in Arizona.

Due to these various excitations, PN spectra provide a wealth of information of its temperature and density of the gas, as well as the abundances of the elements.

2. METHODOLOGY AND CALCULATIONS

Method of Determining Electron Temperature

Since the strengths of emission lines that produced in gaseous nebulae are very sensitive to the electron temperature the ratio of forbidden emission lines of PN spectra can be used to determine the electron temperatures of the planetary nebulae. For example Kaler (1986) used the ratio of [OIII] and [NII] forbidden lines to determine the electron temperatures of 115 PNs while Osterbock *etal* (2005) has derived the undermentioned ratio of [OIII] at 5007 Å, [OIII] at 4959 Å and [OIII] at 4363 Å (auroral) forbidden lines to determine the electron temperature of low dense planetary nebulae.

$$T_e = -\frac{32990}{Log\left[\frac{7.575}{R_{[OIII]}}\right]} \qquad (1)$$

$$T_e = \frac{14320}{-0.89 + Log[R_{[OIII]}]} \qquad (2)$$

$$T_e = \frac{32900.}{Log[0.120482 R_{[OIII]}]} \qquad (3)$$

$$T_e = \frac{32900.}{Log[0.126584 R_{[OIII]}]} \qquad (4)$$

The above methods, described by Kwok (2007), Kaler (1986), Acker (2001) and Osterbock *et al* (2005) respectively, were used to calculate the electron temperature in this research because all [OIII] forbidden lines are prominent when compared with [NII] forbidden lines in the spectra used for this research. Where,

$$R_{[OIII]} = \frac{I(\lambda\,5007) + I(\lambda\,4959)}{I\,(\lambda\,4363\,)}$$

Method of Determining Electron Densities

Letzia and Kaler (1988) have calculated electron densities of 146 Planetary nebulae by using [OII], [Cl III], [SII] and [ArIV] forbidden lines. It was found that the [OII] densities are generally lower than those from [Cl III], by an average factor of 0.65. A good agreement between [OII] and [SII] ratios were found as 0.95. Saraph & Seaton (1970) and Aller & Epps (1976) also made comparisons among the electron densities in planetary nebulae from different ions.

In this research we have used [SII], $\lambda\ 6716$ and $\lambda\ 6731$, ratios of PN spectra as described below by Acker (2005) to estimate the electron densities.

$$R_{[S\,II]} = \frac{I(6716)}{I(6731)}. \qquad (5)$$

$$R_{[S\,II]} = 1.49\left[\frac{1 + 3.77x}{1 + 12.8x}\right]. \qquad (6)$$

Where $x = 10^{-2}/\sqrt{T_e}$.

Now electron density N_e is given by the following formula.

$$N_e = 10^{-2}\sqrt{T_e}\left[\frac{R_{[S\,II]} - 1.49}{5.62 - 12.8R_{[S\,II]}}\right]. \qquad (7)$$

De-Redden the Observed Spectra

Due to the intervening dust between the observer and the PNs, the effect of interstellar reddening affects the [OIII] and [SII] forbidden lines intensity ratios used for temperature and density calculation of observed spectra. As a result of the interstellar dust reddening the ratio of Balmer lines commonly known as “Balmer decrement” is changed. This is because micron-sized dust particles selectively dim shorter-wavelengths more than they do longer-wavelengths leading to Balmer line ratios that differ systematically from the theoretical predictions. As per Osterbrock & Ferland (2006), under typical conditions in planetary nebulae, the theoretical Balmer decrements are:

$$\frac{H_\alpha}{H_\beta} = 2.86 \text{ or } \frac{H_\gamma}{H_\beta} = 0.47.$$

In order to check whether the spectra of this research are affected by the interstellar dust, the Balmer decrement of the sample spectra were compared with above values, and it was found that all our spectra in sample were affected by the interstellar reddening (see Table 1 and 2)

In order to de-redden the observed spectra in our sample, Whitford extinction function described by Kaler (1986) was used.

$$I_c(\lambda) = I_0(\lambda)10^{cf(\lambda)}. \qquad (8)$$

where,

1. I_c is the de-reddened line intensity and I_0 is the observed intensity with reddened.
2. $f(\lambda)$is known as reddening curve for observed wavelength λ as described by Kaler (1976) in the following.

$$f(\lambda) = 2.5634\lambda^2 - 4.8735\lambda + 1.7636. \quad (9)$$

3. c, the extinction coefficient that can be calculated as,

$$c(H_\beta) = 3.08\log(I(H_\alpha)) - 7.55. \qquad (10)$$

Where $I\ (H_\alpha)$ is the observed intensity of H_α relative to $H_\beta = 100$ by convention. The de- reddened intensity values of forbidden [OIII] and [SII] were used to calculate the electron temperatures and density respectively in our sample of 16 planetary nebula spectra.

3. RESULTS

Table 1. The observed Balmer decrement and un-reddened Balmer decrement

Name	Experimental Value H_α/H_β	Theoretical Value H_α/H_β	Difference $\|d\|$
NGC2346	0.40177665	2.86	2.458223
NGC2392	0.349821022	2.86	2.510179
NGC2371	0.402126822	2.86	2.457873
NGC2438	0.243537061	2.86	2.616463
NGC6058	0.524066577	2.86	2.335933
NGC6537	0.127973464	2.86	2.732027
NGC6543	0.202366218	2.86	2.657634
NGC6563	0.247916667	2.86	2.612083
NGC6565	0.311614731	2.86	2.548385
NGC6567	0.113352839	2.86	2.746647
NGC6741	1.172810281	2.86	1.68719
NGC6751	0.157275132	2.86	2.702725
NGC6905	0.085309901	2.86	2.77469
NGC2440	0.274412721	2.86	2.585587
IC289	0.186716539	2.86	2.673284
M57	0.367807446	2.86	2.492193

Table 2. The extinction coefficient (C).

Name	C
NGC2346	-0.17027
NGC2392	0.014955
NGC2371	-0.17144
NGC2438	0.49938
NGC6058	-0.52571
NGC6537	1.360071
NGC6543	0.747095
NGC6563	0.475538
NGC6565	0.169657
NGC6567	1.522348
NGC6741	-1.60322
NGC6751	1.084287
NGC6905	1.902522
NGC2440	0.339715
IC289	1.39910809
M57	-0.05211

Electron Temperatures

We have calculated the $R_{[OIII]}$ values for each planetary nebula in our sample (See the table 3).Then electron temperatures were calculated independently from above (1), (2), (3) and (4) equations.

Table 3.[OIII] Ratio values.

Name	R[OIII]
NGC2346	36.33579
NGC2392	60.15652
NGC2371	87.03611
NGC2438	66.93878
NGC6058	32.34378
NGC6537	55.49495
NGC6543	293.8021
NGC6563	112.3536
NGC6565	172.6705
NGC6567	54.59635
NGC6741	77.53829
NGC6751	76.08837
NGC6905	37.97054
NGC2440	62.29644
IC289	30.02491
M57	114.7267

Table 4.Electron temperatures (K).

Name	Kwok T_e (K)	Kaler T_e (K)	Acker T_e (K)	Osterbrock & Ferland T_e (K)
NGC2346	21041.56	21362.47	22281.71	21560.47529
NGC2392	15921.84	16102.87	16610.34	16206.20168
NGC2371	13512.91	13642	13999.6	13711.41622
NGC2438	15141.19	15304.41	15760.31	15396.02096
NGC6058	22728.71	23104.57	24188.22	23340.63143
NGC6537	16566.75	16763.17	17315.46	16876.73471
NGC6543	9018.705	9074.463	9224.34	9098.341668
NGC6563	12233.48	12338.59	12627.64	12392.70342
NGC6565	10551.96	10629.31	10839.73	10666.15608
NGC6567	16703.68	16903.46	17465.52	17019.25726
NGC6741	14184.25	14326.93	14723.54	14405.12649
NGC6751	14300.32	14445.41	14848.98	14525.17713
NGC6905	20467.07	20770.28	21636.83	20956.10981
NGC2440	15657.7	15832.6	16322.29	15931.88331
IC289	23956.59	24375.23	25587.74	24641.15522
M57	12139.39	12242.83	12527.14	12295.89386

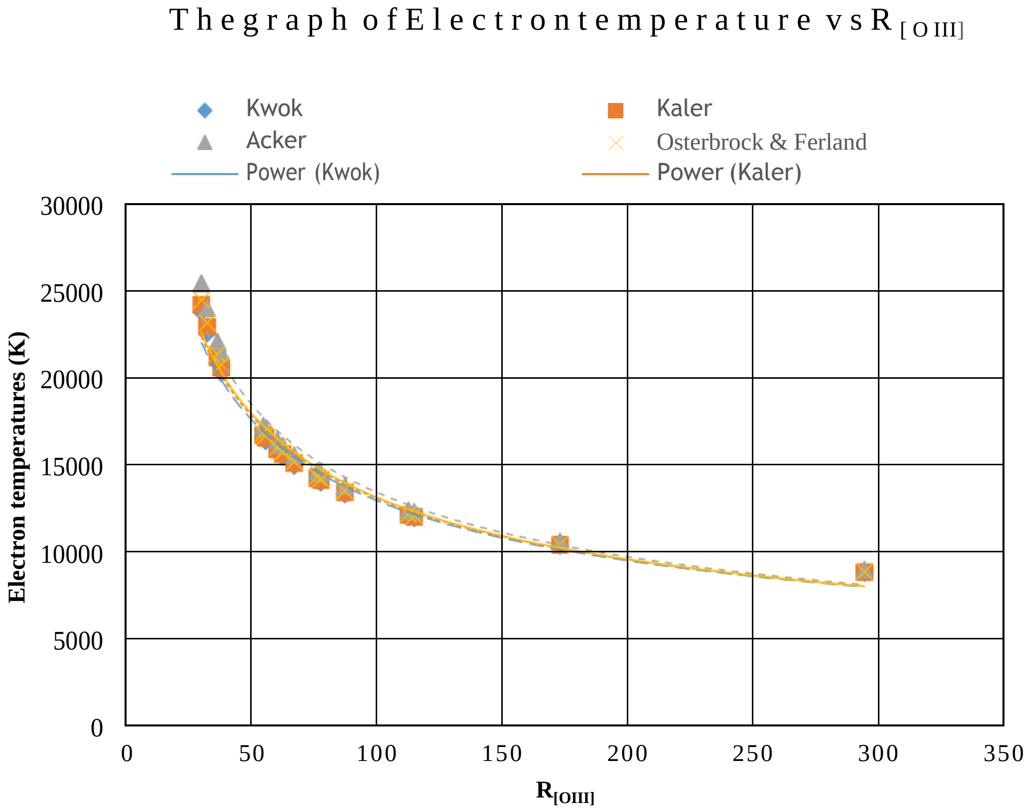

Figure 1. The correlation between the electron temperature and the $R_{[OIII]}$ for each method given in four different equations

A relationship between average electron temperatures (see table 5) and [OIII] ratio was obtained (figure 2) as a new model to determine the electron temperature of a PN for given [OIII] ratio (see the equation 12).

Table 5. Average Electron temperatures (K)

Name	Average Electron Temperature(K)
NGC2346	21682.03305
NGC2392	15798.45427
NGC2371	13748.82331
NGC2438	15137.05187
NGC6058	23340.53064
NGC6537	16354.4802
NGC6543	9006.693454
NGC6563	12595.76197
NGC6565	10892.88016
NGC6567	16474.46833
NGC6741	14326.97543
NGC6751	14425.80875
NGC6905	20641.73804
NGC2440	15573.78738
IC289	23329.09236
M57	12507.16901

The fitted model for the above relationship is,

$$R_{[OIII]} = 32.343 + 5104.149e^{-0.000329925205T_e} \tag{12}$$

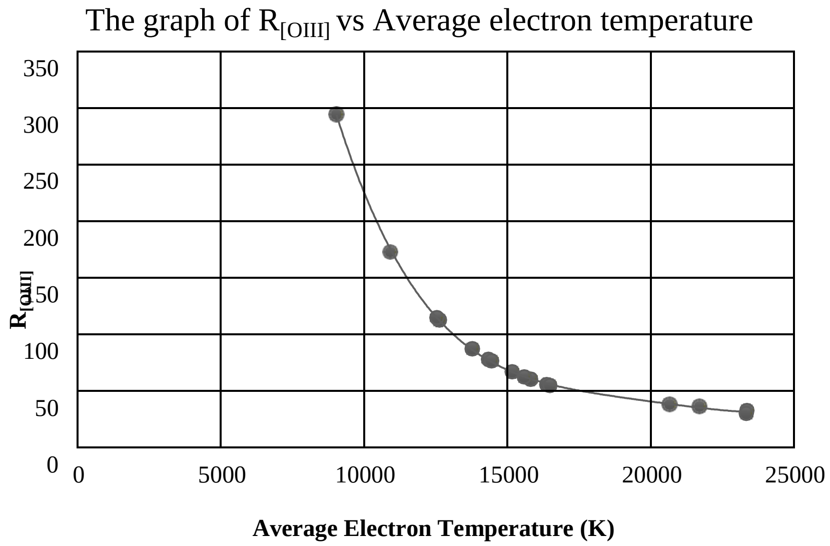

Figure 2. The fitted model for the graph of R[OIII] vs average electron temperature.

Hence an expression can be obtained to estimate electron temperature from the [OIII] line ratios as follows.

$$T_e = -3030.3030 \ln\left(\frac{|R_{[OIII]} - 32.34351|}{5104.15}\right)$$

(13)

The Electron Densities

From the average electron temperatures and the [SII] line ratios the electron densities for each planetary nebula were evaluated by the equation 7 (see the Table 6).

Table 6. Electron Densities

Name	[S II] Ratio	Average Electron Temperature (K)	Electron Density (cm^{-3})
NGC2346	0.499588498	21682.03305	18584.39543
NGC2392	0.833636922	15798.45427	1628.100553
NGC2371	0.904967876	13748.82331	1146.802707
NGC2438	1.415385025	15137.05187	73.29270112
NGC6058	1.261398003	23340.53064	487.4664244
NGC6537	0.535561861	16354.4802	9796.747258
NGC6543	0.674777301	9006.693454	2552.841711
NGC6563	1.009735715	12595.76197	735.8614294
NGC6565	0.710689579	10892.88016	2329.844695
NGC6567	0.647489779	16474.46833	4033.791007
NGC6741	0.530435506	14326.97543	9731.997869
NGC6751	0.870731301	14425.80875	1341.905529
NGC6905	1.009241954	20641.73804	943.7972179
NGC2440	0.758218474	15573.78738	2227.18599
IC289	1.118653582	23329.09236	650.3616977
M57	1.014953345	12507.16901	718.7391972

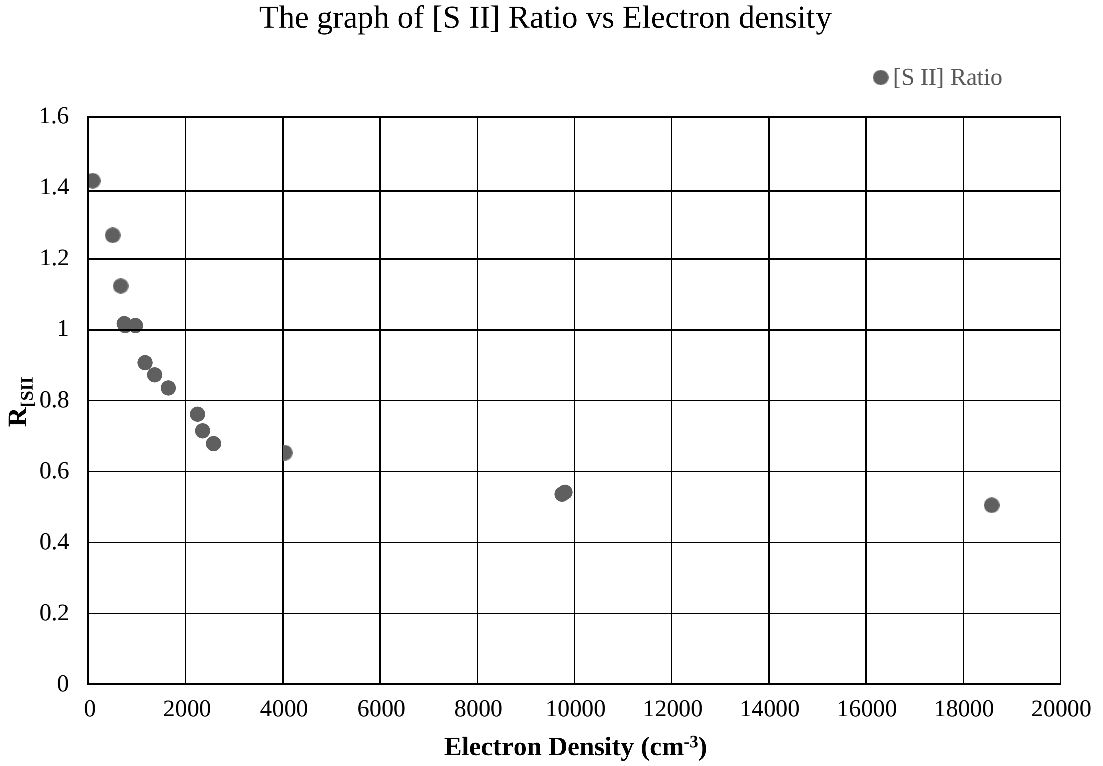

Figure 3. $R_{[SII]}$ variation with respect to the electron densities

4. CONCLUSIONS

A sample of 16 planetary nebulae was selected and their electron temperatures and electron densities were calculated. It was found that all the PNs in the sample were affected by interstellar reddening. Using Whitford extinction function, all PNs were de-reddened. Four methods were used to determine the electron temperatures of these PNs. The calculated electron temperatures were averaged and $R_{[OIII]}$ ratios were plotted against them. A good mathematical relationship was found between $R_{[OIII]}$ ratios and electron temperatures, and the obtained relationship can be used to determine the unknown electron temperatures from given [OIII] ratios. The standard deviation of the averaged electron temperatures is 1.109 and the RMS value of the model is 0.679. Since the electron temperatures of all PNs in the selected sample are greater than 10000K, this mathematical relationship should be tested for the lower electron temperature planetary nebulae as a future work. Another significance of this relationship is that for higher electron temperatures such as beyond 24000K, the $R_{[OIII]}$ value becomes constant. This concludes that, for higher electron temperatures, $R_{[OIII]}$ will reach its minimum value. The electron densities were also determined for this selected sample of planetary nebulae.

Depending on the Average Electron temperatures, we have evaluated the electron densities via the method of [SII] ratios. From the graph of [SII] ratio vs electron density it can be observed that the numerical validity of [SII] is varying between 0.5 and 1.5. Although the scatter plot shown in Figure 3 had been drawn for different electron temperatures, it can be observed a curvature of the function to be fitted (Figure 3) in the relationship between [SII] ratio and electron density. The Pearson correlation of [SII] and electron density is -0.717, which is a strong correlation.

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