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HELIUM RECOMBINATION LINES AS A PROBE OF ABUNDANCE AND TEMPERATURE PROBLEMS

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RESUMEN

Se presenta una fórmula simplificada para determinar una temperatura electrónica T_e(He I), para nebulosas planetarias (NPs) usando el cociente de flujos He I λ7281/λ6678. En nuestros estudios previos de T_e(He I) (Zhang et al. 2005), usamos los coeficientes de emisión de líneas He I dados por Benjamin et al. (1999). Aquí examinamos los resultados de usar datos atómicos más recientes presentados por Porter et al. (2005). Se encuentra acuerdo, lo que sugiere que las incertidumbres en los datos atómicos en la T_e(He I) resultante, es despreciable. También presentamos una fórmula analítica para derivar la temperatura electrónica usando la discontinuidad a 3421 Å del He I Nuestro análisis muestra que los valores de T_e(He I) son significativamente menores a las temperaturas electrónicas T_e(H I) deducidas de la discontinuidad de Balmer del espectro de recombinación del H I y a las inferidas de las líneas excitadas colisionamente del cociente de flujos de líneas prohibidas del [O III], T_e([O III]). Adicionalmente, T_e(H I) cubre un rango más amplio de valores que T_e(He I) o que T_e([O III]). Esto apoya el modelo nebular de dos abundancias con material deficiente en hidrógeno embebido en gas difuso de composición química "normal" (i.e. $\sim$ solar).

ABSTRACT

The paper presents a simplified formula to determine an electron temperature, T_e(He I), for planetary nebulae (PNe) using the He I λ7281/λ6678 line flux ratio. In our previous studies of T_e(He I) (Zhang et al. 2005), we used the He I line emission coefficients given by Benjamin et al. (1999). Here we examine the results of using more recent atomic data presented by Porter et al. (2005). A good agreement is shown, suggesting that the effect of uncertainties of atomic data on the resultant T_e(He I) is negligible. We also present an analytical formula to derive electron temperature using the He I discontinuity at 3421 Å. Our analysis shows that T_e(He I) values are significantly lower than electron temperatures deduced from the Balmer jump of H I recombination spectra, T_e(H I),and that inferred from the collisionally excited [O III] nebular-to-auroral forbidden line flux ratio, T_e([O III]). In addition, T_e(H I) covers a wider range of values than either T_e(He I) or T_e([O III]). This supports the two-abundance nebular model with hydrogen-deficient material embedded in diffuse gas of a "normal" chemical composition (i.e. $\sim$ solar).

Key Words: **PLANETARY NEBULAE**

1. INTRODUCTION

There are two long-standing problems in nebular astrophysics that are termed the "abundance problem" and the "temperature problem". The abundance problem refers to the findings that when the heavy element abundances are measured, particularly in planetary nebulae (PNe), the results derived from collisionally excited lines (CEL) are often lower than those derived from optical recombination lines (ORLs). One manifestation of the temperature problem is that electron temperatures deduced from the collisionally excited [O III] nebular-to-auroral forbidden line ratio – hereafter T_e([O III]) – are systematically higher than those determined from the Balmer jump (BJ) of H I recombination spectrum – hereafter T_e(H I) (see Liu 2004 for a recent review). Some recent attempts to solve these problems have implications that PNe may have complex physical conditions which are far from being understood. A correlation between the abundance discrepancies and the temperature discrepancies is found by Liu et al. (2001), suggesting that the two problems may have a common origin. Two possible solutions are **a)** the presence of temperature and density variations within chemically homogeneous nebulae (Peimbert 1967; Viegas & Clegg 1994) and **b)** a two-abundance nebular model with hydrogen-deficient material embedded in diffuse gas of a "normal" chemical composition (i.e. $\sim$ solar) (Liu et al. 2000). To further investigate the problems, more methods to probe nebular physical conditions are obviously valuable.

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In an earlier paper (Zhang et al. 2005, hereafter Z05), we presented a method to use He I recombination lines to measure electron temperatures of PNe – hereafter T_e(He I). We studied the effect that temperature and density variations inside nebulae have on the T_e(He I) value and found that for a chemically homogeneous nebula, the possible presence of temperature and density variations causes T_e(He I)$\gtrsim T_e$(H I). In contrast, the two-component nebular model predicts T_e(He I)$<T_e$(H I). Therefore, a comparison between T_e(He I) and T_e(H I) provides an opportunity to discriminate between the two paradigms. Applying the method to a sample of PNe, we found that T_e(He I) values are significantly lower than T_e(H I) values, in agreement with the prediction of the two-component (also called two-abundance) nebular model.

This paper is an extension of Z05. In Section 2, we present an analysis formula to derive T_e(He I). In Section 3, we give a statistical discussion of T_e(He I), T_e(H I) and T_e(O III).

2. METHOD

In order to derive T_e(He I), we use analytic formulae for the emissivities of He I lines as a function of electron temperature given by Benjamin et al. (1999). We suggested that the He I λ7281/λ6678 intensity ratio serves as the best line ratio suitable for temperature determinations (Z05). A non-linear equation, $I(7281)/I(6678) = f(T_e)$, was used in Z05 to determine T_e(He I).

However, we find that when $T_e < 15000$ K, there is a simple linear relationship between T_e(He I) and the He I λ7281/λ6678 intensity ratio, as shown in Fig. 1. With an electron density $N_e = 10^4$ cm^{-3}, a least-squares fit yields the following relation

$$T_e(\text{He I}) = 49300 \times \frac{I(7281)}{I(6678)} - 2150 \text{ K}. \qquad (1)$$

The relation is quite insensitive to electron density. We thus recommend equation 1 as a general formula to determine T_e(He I) for $T_e < 15000$ K. Considering the uncertainties of electron density, the maximum systematical errors of T_e(He I) derived by equation 1 is 7%. In Fig. 2 we compare the T_e(He I) derived from equation 1 and those derived by Z05 using the non-linear equation mentioned above. An excellent agreement is indicated.

Recently, based on improved atomic data, Porter et al. (2005) presented new calculations of He I line emissivities. They claimed that for the 32 He I emission lines they considered, the average difference between the new He I emissivities and those of Benjamin et al. (1999) is 4.6%. In Fig. 1 we overplot the values obtained according to Porter et al. (2005) (cf. their Table 1). A good agreement between the two sets of data is shown, implying that there is hardly any effect of the uncertainties of He I emissivities on the temperature determination from the He I λ7281/λ6678 intensity ratio.

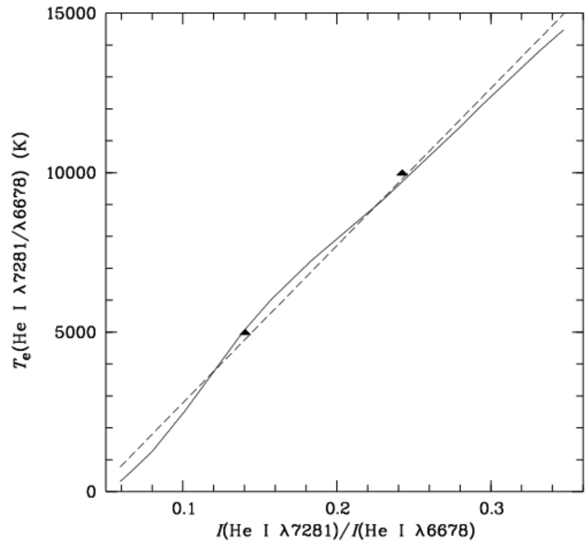

Fig. 1. Electron temperature is plotted against the He I λ7281/λ6678 intensity ratio for an electron density of 10^4 cm^{-3}. The solid line shows the prediction based on the atomic data given by Benjamin et al. (1999). The dashed line is a linear fit (see equation 1). The triangles represent the prediction based on the more recent calculation of Porter et al. (2005).

The determination of T_e(He I) is based on the assumption of Case B for the He I lines. An important consideration, therefore, is whether the possible departure from pure Case B to Case A recombination for the He I singlet lines may affect temperature determination. In Z05, we also used the He I λ7281/λ5876 intensity ratios to determine electron temperatures, which are found to be in good agreement with those derived from the He I λ7281/λ6678 ratios. Given the argument that the deviation from Case B has a different effect on the He I λ7281 and the He I λ5876 lines, we suggest that the effect is negligible.

Another method to measure T_e(He I) is to use the He I discontinuity at 3421 Å, produced by He$^+$ recombinations to the He I 2p ^{3}P^o level. A relation between the He I discontinuity at 3421 Å and electron

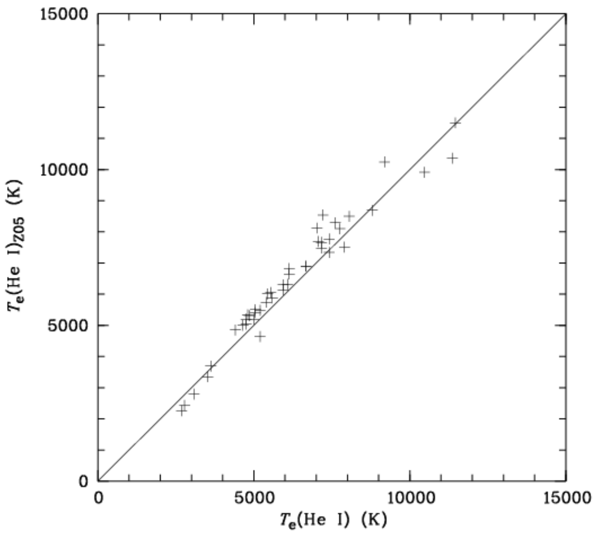

Fig. 2. Comparison of the T_e(He I) derived from equation 1 and those derived by Z05. The solid line is a $y = x$ plot.

temperature is derived as,

$$T_e(\text{He I}) = (2267 \pm 46) \times \left[\frac{\Delta I(3421)}{I(3613)}\right]^{-3/2} K, \quad (2)$$

where $\Delta I(3421)/I(3613) = [I(\lambda3421^-) - I(\lambda3421^+)]/I(\text{He I } \lambda3613)$. The observation of the He I λ3421 discontinuity, however, is very difficult due to its weakness. In this paper, we present only a fit relation between this discontinuity and electron temperature. The application of this method to PNe is beyond the scope of this paper. We note that to apply this method, high quality spectroscopic observations of this discontinuity are required.

3. RESULTS AND DISCUSSION

We calculate T_e(He I) for 48 PNe. Our results show that T_e(He I)$\lesssim T_e$(H I)$\lesssim T_e$([O III]). The average values for the sample PNe are T_e(He I)$= 6300 \pm 2100$ K, T_e(H I)$= 10300 \pm 3100$ K, and T_e([O III])$= 11900 \pm 2600$ K. The result is exactly opposite to the predictions of the scenarios of temperature fluctuation and density inhomogeneities but in good agreement with the expectations of the two-abundance nebular model proposed by Liu et al. (2000).

Fig. 3 shows the distribution of T_e(He I), T_e(H I) and T_e([O III]). Inspection of Fig. 3 shows that except for a few extreme cases, T_e([O III]) falls between 9000 and 15 000 K, and T_e(He I) falls between 3000 and 9000 K, whereas T_e(H I) covers a wider range, varying from 5000 to 15000 K. In the scenario of the two-component nebular model, the H-deficient component is extremely cold so that no CELs arise but ORLs are heavily enhanced. Therefore, T_e(He I) and T_e([O III]) characterize the H-deficient cold gas and the diffuse hot gas, respectively. Due to its hydrogen deficiency, the ultra-cold ionized gas has much less of a contribution to the H I recombination spectrum than the He I recombination spectrum. Accordingly, T_e(H I) is a weighted average over both regions. As a result, T_e(H I) covers a wider range of values than T_e(He I) or T_e([O III]).

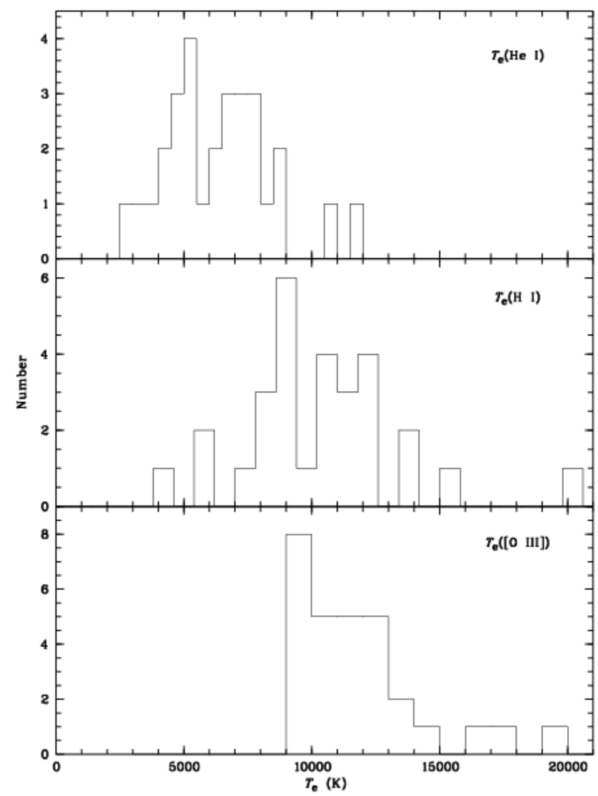

Fig. 3. Histograms showing the numbers of PNe with a given T_e(He I) (upper panel), T_e(H I) (middle panel) and T_e([O III]) (lower panel).

In previous studies of a large sample of PNe (Zhang et al. 2004), we have found that the discrepancies between T_e(H I) and T_e([O III]) are anticorrelated with electron densities, i.e. high-density nebulae have the smallest temperature discrepancies. Robertson-Tessi & Garnett (2005) found a negative correlation between the CEL/ORL abundance discrepancies and the nebula diameter and the Balmer surface brightness, suggesting that bright and compact PNe have small CEL/ORL abundance discrepancies. Given that the abundance discrepancies are positively correlated with the temperature discrepancies (Liu et al. 2001), the two findings are mutually consistent. We thus infer that the abundance and temperature discrepancies are related to nebular evolution; with expansion of nebulae, the contribution from the H-deficient material to recombination spectra becomes increasingly important. Here we compare the discrepancies between T_e(He I) and T_e(H I) against nebular densities and CEL/ORL abundance discrepancies. However, no prominent correlation is seen, implying that some properties of the postulated H-deficient inclusions which dominate T_e(He I), such as its helium composition, are very different for different PNe. To further understand the H-deficient inclusions, high S/N ratio, high spectral resolution spectroscopy of ORLs from heavy elements is required.

The presence of H-deficient inclusions may have an important influence on the determination of the He/H abundance. Based on a large sample of PNe, Z05 estimated that the filling factor of H-deficient components has a typical value of 10^{-4}, which may cause the He^+/H^+ ionic abundance ratio to be overestimated by a factor of $\sim$1.25. The estimation, however, is based on a very simple assumption, that the H-deficient inclusions in all PNe have identical properties to those given by Péquignot et al. (2003) in constructing two-abundance photoionization models of NGC 6153. Further spectroscopy of PNe should provide more constraints on the physical conditions of the H-deficient inclusions.

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