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Editors: William H. Lee and Silvia Torres-Peimbert

THE O II RECOMBINATION LINE ABUNDANCE PROBLEM IN PLANETARY NEBULAE

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RESUMEN

Presentamos observaciones de líneas de recombinación de O II en diez nebulosas planetarias brillantes, y mediciones de O II y [O III] con resolución espacial en NGC 6720. Esto es con el fin de estudiar la discrepancia entre las abundancias calculadas con líneas de recombinación de O II y aquellas derivadas de líneas de excitación colisional de [O III]. Observamos una gran variación en la discrepancia, desde tener resultados consistentes hasta una diferencia de un factor de seis. La magnitud de esta discrepancia esta anti-correlacionada con el brillo superficial de la nebulosa (aquellas que son compactas y más brillantes tienen las menores variaciones). Los niveles de O II poblados a través de recombinación di-electrónica dan abundancias mayores que otros niveles. Nuestra observación en rendija larga muestra que la emisión en O II tiene su máximo al *interior* de la cáscara brillante donde [O III] y Hβ son más brillantes. Con base en las correlaciones observadas, proponemos que la intensa emisión en líneas de recombinación en nebulosas planetarias proviene de recombinación di-electrónica aumentada en el interior de la nebulosa, la cual posiblemente esté impulsada por un viento estelar caliente.

ABSTRACT

We present new observations of O II recombination lines in ten bright planetary nebulae, along with spatially-resolved measurements of O II and [O III] in the Ring nebula NGC 6720, to study the discrepancy between abundances derived from O II recombination lines and those derived from collisionally-excited [O III]. We see a large range in the difference between O II- and [O III] derived abundances, from no difference up to a factor six difference. The size of this discrepancy is anti-correlated with nebular surface brightness; compact, high-surface-brightness nebulae have the smallest discrepancies. O II levels that are populated mainly by dielectronic recombination give larger abundances than other levels. Finally, our long-slit observation of the Ring nebula shows that the O II emission peaks *interior* to the bright shell where [O III] and Hβ are strongest. Based on the observed correlations, we propose that the strong recombination line emission in planetary nebulae is a result of enhanced dielectronic recombination in hot gas in the nebular interior, perhaps driven by a hot stellar wind.

Key Words: **ISM: INDIVIDUAL: RING NEBULA — PLANETARY NEBULAE: ABUNDANCES**

1. INTRODUCTION

Measurements of physical conditions and heavy–element abundances in photoionized nebulae rely heavily on bright, collisionally–excited forbidden lines (FLs). However, abundances derived in this way are sensitive to systematic errors in electron temperature and to deviations of temperature from homogeneity because of the exponential temperature dependence of forbidden–line emissivities, as pointed out by Peimbert (1967).

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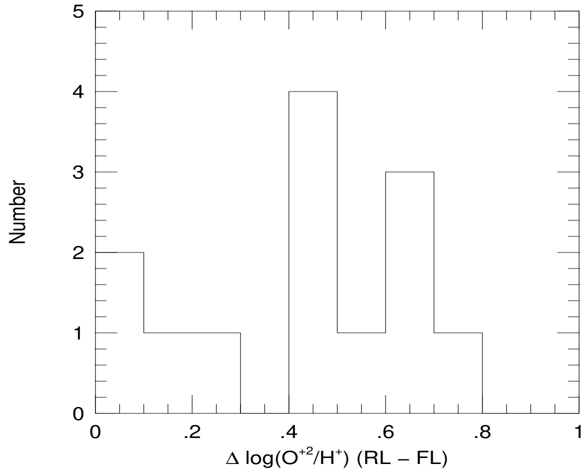

Fig. 1. Histogram of the difference between O^{+2} abundance derived from O II and that derived from [O III] in logarithmic units.

Recent observations of recombination lines (RLs) in a few nebulae (Peimbert, Storey & Torres–Peimbert 1993; Esteban et al. 1998) have called into question the standard forbidden line abundance analysis. These studies have found that recombination lines give significantly higher abundances than the forbidden lines. The common explanation is that the discrepancies are due to temperature fluctuations, which cause the forbidden lines to underestimate the true abundances. However, in some cases (e.g., Liu et al. 1995) the discrepancy between RL abundances and FL abundances is so large that the temperature fluctuation explanation is difficult to accept. Therefore, it is necessary to study the recombination lines in more detail.

One problem has been that few nebulae have been studied in RL emission, so that the systematics of RL emission variations are virtually unknown. Here we report results from two new studies designed to examine RL emission from a moderately–sized sample of PNe (Dinerstein, Lafon & Garnett 2001, in preparation; Garnett & Dinerstein 2001, in preparation), in order to understand better the RL–FL abundance discrepancy.

2. NEW OBSERVATIONS OF O II IN PNE

We observed O II recombination lines in the 4100–4700 Å region of ten bright PNe with the Large Cassegrain Spectrograph on the 2.7 m reflector at McDonald Observatory. We extracted 1-D spectra of these objects to study the O II lines at high signal/noise. The results are presented here. In addition, we obtained spatially–resolved long–slit data for both O II and [O III] lines in eight PNe (six in common with the McDonald sample) using the B&C spectrograph on the 2.4 m Bok reflector at Steward Observatory. These observations covered

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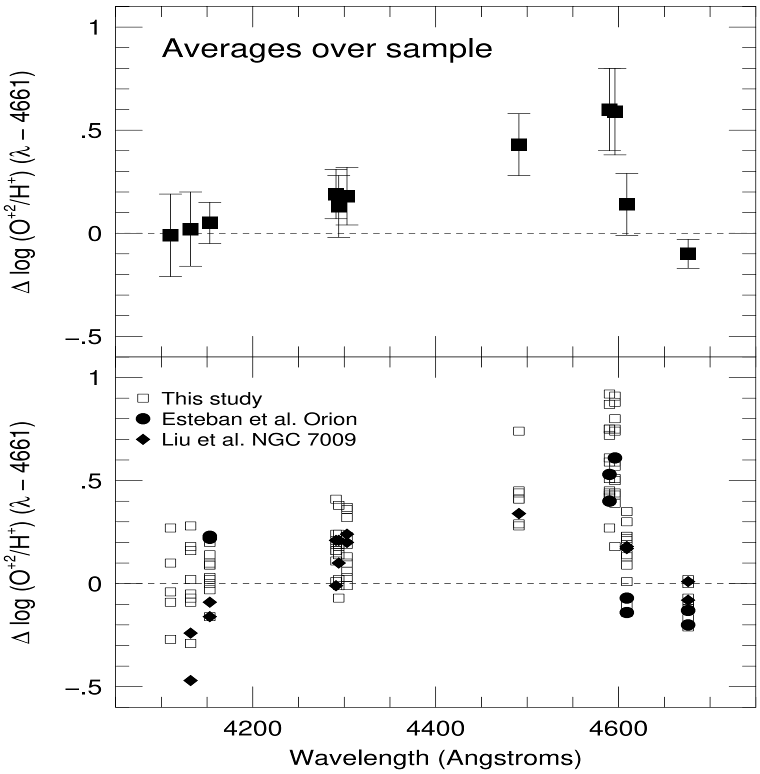

Fig. 2. The logarithmic difference between O^{+2} abundances from O II $\lambda4661$ and that derived from O II lines in other multiplets. The largest difference is seen for the multiplet 15 lines at 4590, 4596 Å.

the 4150–5000 Å region at 2 Å resolution, similar to that of the McDonald spectra. Here we present the results for one object, the Ring nebula NGC 6720.

3. RESULTS

Figure 1 shows a histogram of the differences in O^{+2} abundances derived from O II and [O III] in the McDonald PN sample. We see a large spread in $\Delta(O^{+2}/H^{+})$, ranging from 0.0 to 0.8 dex. Thus, the RL–FL discrepancy is not seen in all nebulae.

Next, we looked at the RL abundances by multiplet. The results are shown in Figure 2, where we show the derived abundances for various O II lines relative to that derived from O II $\lambda4661$. The lower panel shows the individual results, while the upper panel shows the differences averaged over the entire sample. The figure shows that in most cases, the O II lines give similar abundances. There are some notable exceptions, however, in particular the lines from multiplet 15 at 4590, 4596 Å. The abundances from these lines are on average 0.6 dex greater than those derived from the 4661, 4676 Å lines of multiplet 1. The $3p\ ^2F^o$ level from which multiplet 15 arises is populated mainly by dielectronic recombination. We computed the abundances using the dielectronic recombination coefficients of Nussbaumer & Storey (1984), yet we see a large discrepancy with respect to other O II lines. This suggests that either the dielectronic recombination coefficients are underestimated, or that another contribution to dielectronic recombination operates within the affected PNe.

Another intriguing correlation is shown in Figure 3, where we show the difference between RL and FL

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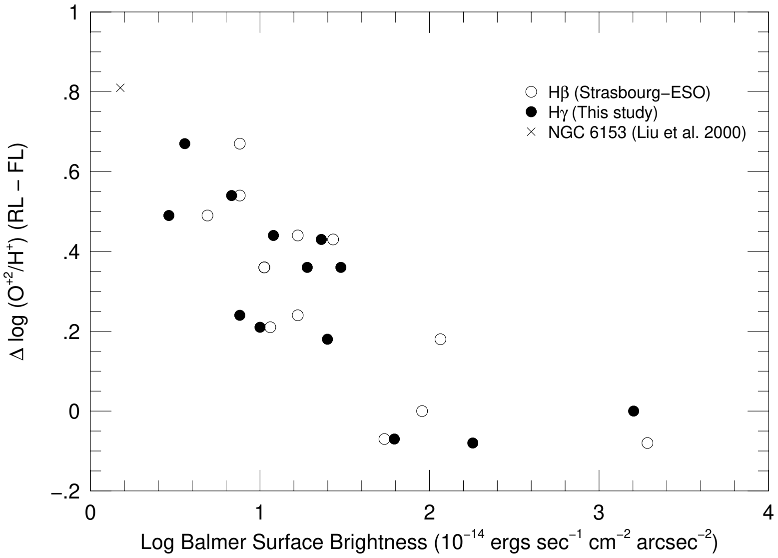

Fig. 3. The difference between O^{+2} abundances from O II and that derived from [O III], plotted against nebular surface brightness.

abundances plotted against the Balmer line surface brightness, which corresponds to the emission measure. We see that the abundance discrepancy is tightly anti–correlated with the nebular surface brightness. Similarly, we find that the abundance discrepancy correlates with nebular diameter, such that the largest PNe show the largest discrepancy between RL and FL abundances. Compact, high–surface–brightness nebulae show little discrepancy between RL and FL abundances. This suggests to us that the abundance problem is a function of PN evolution, pointing to some physical process that is related to the evolutionary state of the nebula.

We now show some results from our spatially–resolved long–slit observations of O II and [O III] in the Ring nebula NGC 6720. Figure 4 shows the spatial distribution of the Hβ, [O III] λ4959, and O II λ4661 fluxes along the slit. For reference, the slit was aligned east–west and centered on the central star, which is located at pixel 66 in the figure. We see from this plot that the O II and [O III] emission are distributed very differently in the nebula. While the [O III] emission is distributed similarly to the Hβ emission, the O II emission actually peaks *inside* both [O III] and Hβ. If the O II emission is produced mainly by radiative recombination, however, we would expect the emission to peak *outside* the [O III] region, in the transition from O^{+2} to O^{+}. From these measurements we derived the O^{+2}/H^{+} abundance ratio from both the RL and the FL along the slit. We see a large discrepancy between the RL abundance and the FL abundance in the central region of the nebula. The discrepancy decreases as one moves outward into the bright nebular shell. A similar result was found for the

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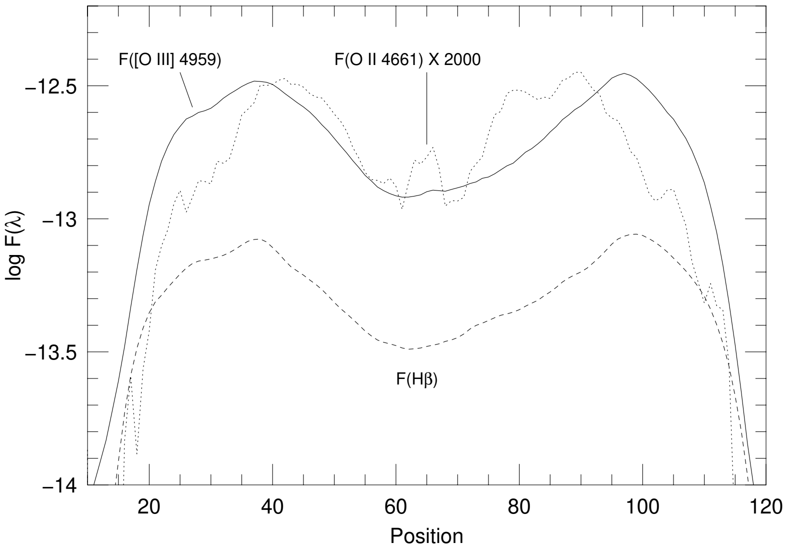

Fig. 4. Log F(λ) for [O III] 4959 Å (*solid line*), Hβ(*dashed line*), and O II 4661 Å (*dotted line*) as a function of slit position across the Ring nebula. The λ4661 fluxes have been multiplied by 2000 to aid the comparison. The position is given in pixels, corresponding to $0\farcs86$ per pixel. The central star is centered at pixel 66.

PN NGC 6153 (Liu et al. 2000).

4. DISCUSSION AND SPECULATION

Our new observations provide hitherto unsuspected clues as to the cause of the discrepancy between RL and FL abundances. The discrepant abundances from multiplet 15 (Figure 2) suggests that dielectronic recombination plays a larger role than previously suspected. The remarkable correlation with nebular surface brightness in Figure 3 suggests that the cause of the RL–FL discrepancy is related to the evolutionary state of the PN; larger, low average surface brightness PNe show the largest differences between RL and FL abundances. The spatial distribution of the O II 4661 Å line in Figure 4 suggests that some physical process in addition to radiative recombination contributes to the O II emission.

Can temperature fluctuations account for what we see? In order to force the [O III] lines to give the same abundances as O II in the Ring nebula, the mean T_e in the central regions would have to be reduced from the observed 12,000 K to 7000 K, while increasing outwards to about 10,000 K in the main shell. Such a thermal structure would be at odds with ionization models for PNe with very hot ionizing central stars, unless the central nebula is very metal–rich. However, we see no central enhancement of He, which might be expected in such a case. Similarly, Liu et al. (2000) find that it is difficult to account for their observations of NGC 6153 with the temperature fluctuation model. They find from new observations made with *ISO* that IR fine–structure lines in NGC 6153 yield ion abundances similar to those obtained from the optical forbidden lines, consistent with small temperature fluctuations. Liu et al. 2000 propose that the data can be accounted for by a model in which the RLs are emitted by dense, super–metal–rich clumps within the lower density plasma where the FLs arise. While this model provides a natural explanation and gives a good match to the data, it is not clear why such super–metal–rich clumps should appear only in the most evolved nebulae, if our observed correlation with surface brightness truly reflects nebular evolution.

We propose a different model which could account for the observations. We suggest that the RLs in PNe can be enhanced by high–temperature dielectronic recombination to high n levels that is not normally accounted for in nebular analysis. Planetary nebulae have been proposed to evolve through the interaction of a fast central star wind with the slow red giant wind of the progenitor. The fast central wind carves out the central bubble and can generate hot gas. Dielectronic recombination rates for various ions actually peak at log $T_e \approx 5.0 \pm 0.5$, so hot gas at this temperature should show enhanced recombination line emission. As the hot bubble expands, more of the nebula will show enhanced recombination line emission, which would account for the correlation of the abundance discrepancy with nebular size, and for the peaking of the RL emission interior to the [O III] region. A test of this model would be to look for a correlation between RL enhancements and the presence of highly ionized species (e.g., O VI) marking the presence of coronal gas.

Whatever the explanation for the discrepancy between RL and FL abundances, a lot of new data will soon be available to test the various models. We can look forward to a greatly improved understanding of this problem.

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