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O^{2+} RECOMBINATION ABUNDANCES IN PLANETARY NEBULAE

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RESUMEN

Presentamos abundancias O^{2+}/H^{+} calculadas a partir de espectroscopía echelle de cuatro nebulosas planetarias, NGC 6210, NGC 6826, Hu2–1 y NGC 6543. Hemos utilizado las líneas prohibidas de excitación colisional, así como líneas permitidas de recombinación. Encontramos que el cociente de las abundancias derivadas de líneas de recombinación a aquellas encontradas con líneas de excitación colisional varían de prácticamente la unidad (1.2 para Hu 2–1) hasta 6.6, para una observación fuera de centro de NGC 6826. Los valores correspondientes de t^2 van de 0.016 a 0.087.

ABSTRACT

We present O^{2+}/H^{+} abundances derived from echelle spectroscopy of four planetary nebulae, NGC 6210, NGC 6826, Hu2–1, NGC 6543, from the forbidden, collisionally excited lines, and from the permitted recombination lines. We find that the ratio of the recombination line to collisional line abundances ranges from essentially unity (1.2 for Hu 2–1) to 6.6, for an offset position of NGC 6826, and corresponding t^2 values range from 0.016 to 0.087.

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

1. INTRODUCTION

Perhaps the most important parameter needed to derive accurate abundances in nebulae is the electron temperature. The classical method of deriving abundances uses the temperature derived from the ratio of collisionally excited lines (e.g. T_e[O III] derived from the 5007/4363Å ratio). These lines, however, have an exponential dependence on temperature and would tend to arise from areas of higher temperature, compared to recombination radiation, which has a more slowly varying temperature dependence. Abundance ratios derived from recombination lines are nearly insensitive to temperature, and provide a more accurate means for deriving abundances compared with the collisionally excited lines. However, discrepancies between the abundances derived from the recombination lines and from the collisionally excited lines up to factors of 10 (e.g. Liu et al. 2000) have been found in a number of nebulae, questioning the validity of (1) the collisional abundances, (2) the recombination abundances, and (3) the fundamental assumptions made about the physics of ionized nebulae. In order to better understand the nature of the discrepancy between the collisional abundances and those derived from recombination lines, we have undertaken a survey of several planetary nebulae (PN) in order to observe the faint recombination lines.

Here we present O^{2+}/H^{+} abundances derived from echelle spectroscopy of four planetary nebulae, NGC 6210, NGC 6826, Hu2–1, NGC 6543, from the forbidden, collisionally excited lines, and from the permitted recombination lines. The observations were made with the 2.3 m telescope at the Observatorio Astronómico Nacional at San Pedro Mártir, in Baja California. For NGC 6210, spectra were obtained from 3 positions within the nebula: at the central star, and 6 and 12 arcseconds south of the central star. For NGC 6826 spectra were obtained for 2 positions within the nebulae: from an ansa 4 arcseconds NW of the central star, and a position 4 arcseconds NE of the central star. For the other objects a single spectrum was obtained at the central star.

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TABLE 1

SUMMARY OF DATA FOR OBJECTS

Object	c(Hβ)	T_e[O III]	n_e[O II]	O^{2+}/H^{2+} (Forbidden)	O^{2+}/H^{2+} (Recombination)
NGC 6210-cs	0.0	9000±100	3.70±0.2	6.27(10^{-4})	1.25±0.15(10^{-3})
NGC 6210-6"S	0.0	9400±100	3.69±0.1	4.82(10^{-4})	9.05±0.18(10^{-4})
NGC 6210-12"S	0.0	9400±100	3.50±0.15	5.51(10^{-4})	1.22±0.24(10^{-3})
NGC 6826-NW ansa	0.25	9200±200	3.20±0.2	3.48(10^{-4})	1.78±0.45(10^{-3})
NGC 6826-4"NE	0.25	9200±200	3.25±0.2	3.53(10^{-4})	2.32±0.58(10^{-3})
Hu2-1	0.36	9900±300	3.8±0.4	1.60(10^{-4})	1.93±0.48(10^{-4})
NGC 6543	0.16	7950±100	3.8	5.69(10^{-4})	2.07(10^{-3})

2. REDUCTION AND ANALYSIS

The spectra were reduced using the *doecslit* package in IRAF, in the standard manner. Fluxes were measured again within IRAF, and gaussian fitting of the weakest features was performed with the DIPSO (Howarth) routine of the STARLINK software collection.

The reddening was derived for these objects by comparing the Balmer decrement to their case 'B' predicted values. The line fluxes were then dereddened using the law of Seaton (1979). The electron temperatures T_e were derived via the [O III] (4959+5007)/4363 Å ratio. The electron densities n_e were derived using the [O II] 3726/3729 Å ratio. The errors on T_e were based on the error for λ4363, and the errors on n_e were based on the intensity errors for the $\lambda\lambda$ 3726, 3729 fluxes.

Abundances for the collisionally excited lines were derived by solving the equations of satistical equilibrium with the program EQUIB, adopting T_e[O III] and n_e[O II]. The errors on the abundances are based on the propagation of T_e(min,max) and n_e(min,max) through the abundance calculations.

Recombination line abundances for O^{2+} were derived using the recombination coefficients of Storey (1994) and the branching ratios of Liu et al. (1995) which take into account the effects of intermediate coupling. The errors on the recombination abundances are based on the flux measurement errors of the lines. The final abundances presented in Table 1 are weighted averages, based on errors.

Table 1 also includes the physical conditions found within these objects, i.e. c(Hβ), electron temperature in degrees Kelvin, and electron density in log of cm^{-3}. O^{2+}/H^{+} ratios are presented for both forbidden and recombination lines.

3. RESULTS AND CONCLUSIONS

We find discrepancies in the O^{2+}/H^{+} ratio derived from recombination lines and from forbidden lines in most objects, outside of the formal error, with the exception of Hu 2–1. Table 2 presents the ratio of the collisional to recombination line abundance for our objects, and other objects in the literature, together with the temperature fluctuation parameter t^2 as originally defined by Peimbert (1967). The recombination to collisional discrepancies have been thought to arise from temperature fluctuations within nebulae, where the collisionally excited lines which have an exponential temperature dependence arise from higher temperature regions than the recombination lines, which tend to trace the whole nebula. The abundances from the collisional lines are thus underestimated. However, Armour and Kingsburgh (2001) have found that the velocity distribution of the forbidden and recombination lines of O^{2+} is identical hence the volume traced by both types of lines is identical. Additionally Liu et al. (2000) have ruled out the idea of temperature fluctuations as the source of this discrepancy, and find that the abundances derived from the optical forbidden lines of NGC 6153 are identical with those derived by the temperature–insensitive IR lines and the UV lines. However in this object, recombination line abundances for a variety of ions can be up to factors of 10 (!) higher than the collisional line abundances. Thus this longstanding problem in nebular astrophysics remains.

TABLE 2

SUMMARY OF T^2 DERIVED FOR PN

Object	O^{2+}(rec)/O^{2+}(coll)	t^2	Ref.
NGC 6826-NW ansa	5.1	0.080	This work
NGC 6826-4"NE	6.6	0.087	This work
Hu2-1	1.2	0.016	This work
NGC 6210-cs	1.9	0.038	Kingsburgh et al. 1997
NGC 6210-6"S	2.3	0.040	Kingsburgh et al. 1997
NGC 6210-12"S	2.2	0.051	Kingsburgh et al. 1997
NGC 6543	3.8	0.057	Kingsburgh et al 1996
NGC 7009	4.7	0.098	Liu et al., 1995
NGC 6572	1.6	0.044	Peimbert, Storey & Torres–Peimbert, 1993
NGC 3242	3.3	0.107	Barlow et al. 2001, in preparation
NGC 3918	2.5	0.108	Barlow et al. 2001, in preparation
NGC 5315	1.9	0.040	Barlow et al. 2001, in preparation
NGC 5882	2.3	0.052	Barlow et al. 2001, in preparation
NGC 6572	1.5	0.035	Barlow et al. 2001, in preparation
NGC 6644	1.9	0.077	Barlow et al., in preparation
NGC 6153	9.3		Liu et al. 2000

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