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PHOTOIONIZATION DUSTY MODELS OF THE PLANETARY NEBULA NGC 6302

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RESUMEN

Utilizando cálculos de fotoionización con polvo, modelamos las líneas infrarrojas de alta excitación de NGC 6302. Este objeto es una nebulosa planetaria bipolar de alta excitación y del tipo I de Peimbert. Encontramos que el incluir polvo resulta en una nebulosa considerablemente más caliente.

ABSTRACT

Using photoionization calculations with dust, we model the high excitation infrared lines of NGC 6302. This object is a high excitation bipolar planetary nebula of Peimbert type I. We find that including the dust results in a significantly hotter nebula.

Key Words: **INFRARED: ISM: LINES — ISM:DUST — ISM: PLANETARY NEBULAE: NGC 6302**

1. INTRODUCTION

New observations of the obscured core of NGC 6302 using infrared grating and échelle spectroscopy (200 km s^{-1} and 15 km s^{-1}, respectively) with the CGS3 and CGS4 infrared camera at UKIRT were recently presented by Casassus, Roche & Barlow (2000, hereafter CRB00). They derive a Paβ emission measure of $\int n^2 dx = 5.6 \times 10^{25}$ cm^{-5}, averaging over the central $3'' \times 3''$. Their infrared emission line spectra span a very wide range in ionization species, up to [Si IX]3.93 μm (see Table 1). Their photoionization model using the code CLOUDY (Ferland 1996) provided a reasonable fit to the coronal lines of NGC 6302 (see column 4 in Table 1), this gives support to photoionization as the dominant excitation mechanism of the lines originating from the core of the nebula. In their spherical model, CRB00 used a constant gas density of $n_e = 1.8 \times 10^4$ cm^{-3} with a uniform filling factor of 0.7 although they did not include internal dust despite having concluded that Al and Mg were highly depleted onto dust grains.

In this work we use the photoionization code MAPPINGS IC (Ferruit et al. 1997) to compute a spherical nebular model in which we take into account the presence of dust grains mixed to the plasma. This allows us to make a detailed comparative study of models with or without dust. Furthermore, we took into account the effect of density stratification as a result of the important radiation pressure in the presence of dust grains (see Table 1) along the scheme developed by Binette et al. (1997). The échelle measurements of CRB00 revealed that the nebula has a filled-in structure and, accordingly, all of our models are characterized by a filling factor of unity. The adopted inner gas density is $n_0 = 2.5 \times 10^4$ cm^{-3} and the size of the inner cavity (R_0) is extremely small as shown below.

2. DEFINING THE PARAMETERS OF THE MODEL

The aim of reproducing the strength of the highest excitation lines (e.g. [Si IX]) constrained us to use a temperature of $T_* = 273000$ K for our blackbody approximation of the energy distribution of the exciting star. Solar abundances were adopted but with gas phase abundances depleted as a result of the internal dust as shown in Table 2. The chosen stellar radius of $R_* = 3.26 \times 10^9$ cm was determined from the requirement that

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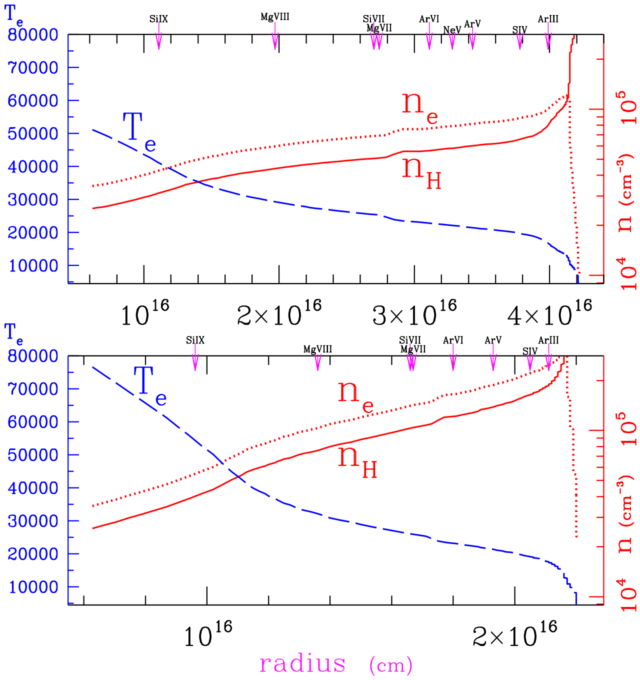

Fig. 1. Top panel: dust–free isobaric model. Bottom panel: dusty model with radiation pressure stratification. On the top axis of both panels, arrows indicate the average depth of representative ions as listed in Table 1.

the bolometric luminosity be L_*=11000 $\mathrm{L}_\odot$, which matches the value favored by Pottasch et al. (1996). The inner ionization parameter starts at a very high value of $U_0 = 1$ which presents the advantage that it ceases being a critical parameter as shown by Binette et al. (1997). This value implies a starting radius,R_0, (or inner empty gas cavity) for the gas which is derived from the condition that

$$U_0 = \frac{Q_H}{4\pi R_0^2} \Big/ n_0 c = 1.0 \, , \tag{1}$$

where $Q_H = 3.9 \times 10^{47}$ quanta/sec is the derived ionizing photon luminosity for our blackbody. We obtain that $R_0 = 5.9 \times 10^{15}$ cm. At larger radii, in the hydrostatic case, the gas density rises due to the integrated radiation pressure while the local ionization parameter, $U(r)$, decreases outward as a result of the rapidly decreasing geometrical dilution factor and of the radially increasing n.

The density stratification due to radiation pressure in our model is determined by the force exerted by absorption of the stellar radiation. We assume a hydrostatic solution in which the gas is *not* accelerated. An important contribution to the gas pressure P is given by the radiation pressure on dust grains and one can write

$$\frac{dP}{dx} = -F_{rad} = -n_D \cdot \int_0^\infty \left(\frac{\varphi_\nu}{h\nu}\right)\left(\frac{h\nu}{c}\right)\sigma_\nu^D d\nu \, , \tag{2}$$

where n_D is the density of grains, σ_ν^D the dust absorption cross section normalized to hydrogen, assuming a solar neighborhood dust–to–gas ratio (see Binette 1998), φ_ν is the impinging *energy* flux from the exciting star and $h\nu/c$ is the momentum exerted by each photon absorbed by grains of mean size $\bar{a}$.

3. DISCUSSION

Our choice of including internal dust is based on two main justifications: the findings of CRB00 which indicate that Al and Mg are depleted and the existence of a bright infrared disk first discovered by Lester

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TABLE 1

MODELED LINE RATIOS.

Observed in NGC 6302			CRB00[a]	Dustfree isobaric model			Dusty stratified model		
Species (1)	λ (μm) (2)	Intensity Ratio[b] – (3)	Intensity Ratio[b] – (4)	Intensity Ratio[b] – (5)	$< n_e^{X+i} >$ (10^4 cm^{-3}) (6)	$< d^{X+i} >$ (10^{16}cm) (7)	Intensity Ratio[b] – (8)	$< n_e^{X+i} >$ (10^4 cm^{-3}) (9)	$< d^{X+i} >$ (10^{16} cm) (10)
[Ne II]	12.81	0.88	0.04	3.63	9	4.13	4.39	20.2	2.17
[Ne III]	15.5	5.6	2.1	11.7	10.8	4.02	5.7	26.7	2.13
[Ne III]	36.0	0.31	0.14	0.46	10.8	4.02	0.19	26.7	2.13
[Ne V]	14.3	10	5.7	9.7	8.03	3.29	7.19	18.6	1.88
[Ne V]	24.2	3.9	1.8	5.45	8.03	3.29	2.49	18.6	1.88
[Ne VI]	7.64	11	8.6	20.02	7.3	2.83	20.27	15.6	1.7
[Mg V]	5.60	0.60	0.30	2.34	8.39	3.49	1.92	20.1	1.95
[Mg VII]	5.51	0.40	0.31	0.85	7.15	2.74	0.97	15.09	1.67
[Mg VIII]	3.03	0.06	0.05	0.1	5.9	1.97	0.13	10.8	1.36
[S III]	18.71	0.30	0.43	0.84	11.07	4.06	0.42	26.6	2.14
[S IV]	10.5	1.52	2.26	5.07	9.4	3.8	2.06	23.2	2.06
[Si VI]	1.96	0.80	0.80	1.12	8.05	3.26	1.07	18.5	1.87
[Si VII]	2.47	0.71	0.32	0.42	7.12	2.71	0.47	15	1.66
[Si IX]	3.93	0.001	0.0012	0.0009	4.3	1.1	0.0011	6.2	0.96
[Ar III]	9.01	0.56	0.33	2.03	10.7	4	1.28	26.2	2.12
[Ar V]	7.92	0.30	0.093	0.57	8.26	3.43	0.44	19.6	1.93
[Ar V]	13.1	0.15	0.076	0.42	8.26	3.43	0.24	19.6	1.93
[Ar VI]	4.53	1.00	1.00	1.00	7.7	3.11	1.00	17.1	1.8
Hβ	0.486			28.8	8.79	3.43	20.61	20.02	1.91
EM[c]		5.6[c]		26.8[c]			47.2[c]		
L(Hβ)[d]		–		1.6[d]			0.70[d]		

[a] Casassus et al. (2000) photoionization model.

[b] Line ratios are expressed relative to [Ar VI]4.53μm, and observed values are taken from CRB00 and Pottash et al. 1996.

[c] Emission measure in units of 10^{25}cm^{-5}.

[d] Hβ luminosity in units of 10^{35}erg s^{-1} for a 4π sterad filled sphere.

& Dinerstein (1984) at 1.25, 2.2, 3.4 and 10 μm. As shown by Binette (1998), radiation pressure can induce a strong density gradient which has the interesting property of producing a richer emission line spectrum encompassing both very high and low excitation lines. Such a radiation pressure requires the presence of dust to be effective. Our results are shown in Figure 1, where we plot the electronic temperature, density and hydrogen density as a function of the nebular radius r. Arrows on the top axis of both panels indicate the mean emission radius of some of the ionic species listed in Table 1. In this figure, there are obvious differences between the traditional dust–free (isobaric) model (top panel) and our dusty density stratified model (bottom panel). The most striking differences are: the density and temperature gradients are much steeper in the dusty case; the Strömgren radius is twice as small in the dusty case since dust absorbs a large fraction of the impinging ionizing radiation; consistently, the Hβ luminosity (Table 1) is twice as low with dust and, finally, the emission measure $\int n_e^2 d$ is twice as high in the dusty case because of the wider range in densities encompassed in the radiation pressure case.

We should point out, however, that the overall fit quality to the emission line ratios is comparable for the three models shown in Table 1 (including that of CRB00, Column 4). The plane–parallel model with dust published by Binette & Casassus (1999) produced a somewhat better fit. This result shows that we cannot define a unique set of input parameters based on the line ratios alone.

An interesting characteristic of the stratified model is that its emission measure exceeds the isobaric model by a factor of $\simeq 2$ which in turns exceed by a factor $\simeq 4$ the value derived by CRB00 who used a constant density of 1.8×10^4. Taking into account our larger inner density, this would account only for a factor two

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TABLE 2

DEPLETED GAS ABUNDANCES[a]

Element	Value
H	1.0
He[b]	0.18
C	1.396×10^{-4}
N	9.127×10^{-5}
O	5.684×10^{-4}
Ne	1.23×10^{-4}
Fe	5.52×10^{-6}
Mg	1.062×10^{-5}
Si	4.353×10^{-6}
S	1.082×10^{-5}
Ca	2.294×10^{-7}
Ar	3.63×10^{-6}

[a] We assume the usual solar neighborhood ISM dust-to-gas ratio (Anders & Grevesse 1989).
[b] The He abundance is enriched to 0.18 relative to H (Ashley & Hyland 1988).

difference. Hence, to bring in agreement our emission measure with the value inferred by CRB00, we need to slice out part of the 4π sterad sphere used in the calculations. This would result in a disklike shape whose aspect ratio (thickness/radius) might be as small as 20%. This would agree with the suggestion of Lester & Dinerstein (1984) of a disk geometry for the dust infrared emission. Needless to say that our model implies a very luminous far infrared dust emission since as much as half of the ionizing energy infalling on our assumed geometrically thin disk would be absorbed by the grains and re–radiated into the far infrared.

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