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PHOTOIONIZATION MODELS FOR PLANETARY NEBULAE WITH INHOMOGENEOUS CHEMICAL COMPOSITION

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RESUMEN

Considerando a la nebulosa planetaria NGC 6153 como prototipo, se demuestra que los modelos de fotoionización que contienen dos componentes con diferentes composiciones químicas pueden reproducir cuantitativamente la mayoría de las características espectrales de esas nebulosas planetarias en las cuales las líneas de recombinación ópticas parecen indicar abundancias mucho mayores que las de las líneas de excitación colisional. Contrariamente a lo que se cree, las líneas de recombinación no reflejan las abundancias nebulares promedio. En particular, las fluctuaciones de composición dentro de la nebulosa planetaria puede producir una sobreestimación de la abundancia de Helio.

ABSTRACT

Considering the prototypical case of NGC 6153, it is shown that photoionization models comprising two components with different chemical compositions can account quantitatively for most of the spectral features of those planetary nebulae in which the optical recombination lines seem to indicate abundances much larger than the collisionally excited lines. Contrary to a common belief, the recombination lines then no longer reflect the average nebular abundances. In particular, fluctuations of composition within PNe may lead to overestimation of the helium abundance.

Key Words: **PLANETARY NEBULAE: ABUNDANCES — PLANETARY NEBULAE: INDIVIDUAL (NGC 6153)**

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Much attention has recently been paid to a class of planetary nebulae (PNe) that present to an extreme degree the so-called "abundance-discrepancy problem" and the associated question of temperature fluctuations (Peimbert 1994; Liu, this volume). The idea that abundance gradients may help to reconcile recombination and collisional lines is not new (Torres-Peimbert et al. 1990). Some empirical toy models illustrating this idea have recently been proposed, but no specific model exists and the only photoionization-model analysis of the effect of abundance gradients on temperature fluctuation diagnostics (Kingdon & Ferland 1998) is surprisingly negative in its conclusions. A thorough analysis of the spectrum and other properties of NGC 6153, the prototype of this class of PNe, is now available (Liu et al. 2000), bringing an impressive set of observational constraints from UV to far IR.

Consider a scenario in which a PN nucleus expels H-deficient material that catches up and eventually mixes with the inner regions of the PN shell. The diffusion time-scale being much longer than the hydrodynamic time-scale, pressure may equilibrate within the gas, yet large composition fluctuations survive for some time. Since gas heating is dominated by photoionization of H and He and cooling by collisional excitation of metastable levels of N, O, Ne ions, and since both materials are subject to the same radiation field, the "H-deficient" ("O-rich") gas will rapidly cool to a temperature of, say, $T \sim 10^3$ K, very low compared to that of the "normal" gas ($T \sim 10^4$ K), then condensing into relatively dense, optically thin "clumps" filling a small fraction of the volume and embedded in the normal gas.

This situation is described in a schematic model, obtained by combining sectors extracted from spherically symmetric calculations:

- A dense H-deficient sector ("Component C_1"), with covering factor $\Omega_1/4\pi$, optical depth τ_1 at 1 Ryd, outer radius R_1, and small filling factor ε_1.
- A normal-composition shell ("Component C_2"), with solid angle 4π, optical depth $\tau_2 > \tau_1$, radius $R_{\rm ext} > R_1$, and filling factor unity, from which is removed the region coinciding with C_1.
- ε_1 is such that the amount of radiation absorbed along a radial path from the inner radius $R_{\rm in}$ to

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R_1 is identical in both components, hence ensuring energy conservation. Then, at any radius between $R_{\rm in}$ and R_1, the total radiation field experienced by each gas is about the same and the absorbing/emitting properties of any parcel of these gases are left approximately unchanged if the gases are now assumed to be intermixed, that is, both the dense clumps and the normal gas are distributed more or less uniformly over 4π between $R_{\rm in}$ and R_1.

- Computations are generally done assuming constant gas pressure, but pressure is not a priori taken as identical in both components.
- The nebula is essentially matter bounded, but [O I] emission led us to include radiation bounded, peripheral clumps, with small covering factor.
- The spectrum of the ionizing star is a taken to be black body, with the flux multiplied by a constant factor f_4 for frequencies above the $\rm He^+$ limit.

Although this model is crude and not fully self-consistent, it is expected to be useful in a preliminary exploration of the properties of bi-abundance PNe.

In the case of NGC 6153, about 56 *independent* observables are available (43 in the optical+UV, 13 in the IR). Apart from $R_{\rm in}$ and the reddening correction (both determined), the model involves 25 parameters and 23 basic spectroscopic constraints (mainly optical). Solutions accounting for the 23 constraints could be obtained for a sequence of values of the two free parameters left, namely the abundances O(C_1) and He(C_2). Some flexibility was allowed for two other parameters to broaden the exploration. These solutions were then evaluated from their $56 - 23 = 33$ spectroscopic predictions, the outer radius of the nebula and the optical stellar continuum in order to decide whether they can be given the status of possible models for NGC 6153. Important results are as follows:

- For a large range of O(C_1), solutions exist that precisely account for all of the optical recombination and collisional lines (including the Balmer jump) used in empirical diagnostics of physical conditions and ionic abundances. Therefore the abundance discrepancy is not apparent in these solutions.
- For O(C_1) $\sim$ 0.03–0.08 by number (10–4% of Hβ arising from C_1), most predictions are in good agreement with observation, the discrepancies—systematically less or much less than a factor of two—being reasonably understandable in terms of observational and theoretical uncertainties. Many IR line fluxes are inaccurate as only a fraction of NGC 6153 falls in the ISO-SWS lobe. Many atomic coefficients are not of ultimate accuracy, especially in the low-T regime that prevails in C_1.
- The gas pressures in C_1 and C_2 are generally found to be within a factor two of each other, giving support to the concept of two gas phases in approximate pressure equilibrium.
- The mass of C_1, the dense "O-rich" component, is small and, despite its very high C-N-O-Ne abundances relative to H, the average abundances are less than twice those of the standard one-component homogeneous model, that fits the optical collisional lines but strongly underpredicts most recombination lines, except the H and He lines.

In this particular configuration, the recombination lines and the "t^2 concept" of temperature fluctuations cannot be used to determine relative abundances, although they are fundamental tools to diagnose and study chemical inhomogeneities. This applies as well to the He lines, once believed to be the most secure and assumption-free tool for abundance determination. NGC 6153 is renowned for its very high He abundance (0.136 according to empirical approaches and homogeneous models), yet good models could be obtained for values as low as 0.09. Paradoxically, the determination of the He abundance will in the end have to rely on the *collisional* contribution to the excitation of some of the He I lines!

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