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PHOTOIONIZATION MODELS FOR GIANT H II REGIONS

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RESUMEN

Revisamos las fuentes de incertidumbre en los modelos de fotoionización de regiones H II gigantes. También discutimos el problema de la temperatura electrónica a la luz de los ajustes de modelos en tres regiones H II gigantes.

ABSTRACT

We review the sources of uncertainties in the photoionization models of giant H II regions. Then we discuss the electron temperature problem, in the light of model fitting experiments of three giant H II regions.

Key Words: **GALAXIES: ABUNDANCES — GALAXIES: ISM — GALAXIES: STARBURST — STARS: EARLY-TYPE — STARS: WOLF-RAYET**

1. INTRODUCTION

Giant H II regions are precious tools for the astronomer for at least two reasons. They reveal the presence of young, massive stars in galaxies and they provide a relatively easy way of measuring the abundances of such elements as He, N, O, Ne up to large distances. Uses of photoionization models for the analysis of giant H II regions have been reviewed recently in Stasińska (1996, 1999, 2000) and will not be repeated here. Roughly speaking, there are three ways of approaching giant H II regions with photoionization models. Grids of ab initio photoionization models can be used to propose and calibrate methods to derive the global properties of the ionizing star clusters and the chemical composition of the surrounding gas (e.g., McGaugh 1994). Comparison of grids of models with samples of observed giant H II regions in well chosen diagrams permits one to infer some general trends in the properties of these objects (see e.g., García-Vargas & Díaz 1994; García-Vargas, Bressan, & Díaz 1995; Stasińska & Leitherer 1996; Dopita et al. this conference). Detailed model fitting of selected giant H II regions may provide more accurate diagnostics if a large number of observational constraints are fitted. An additional advantage of model fitting, although not always recognized, is to test our understanding of the major processes occuring in giant H II regions. One big problem, though, is to appreciate the uncertainties involved in the modelling process. In § 2, we will briefly review the main sources of uncertainties. In § 3, we will present three model fitting experiments with emphasis on the inability of the models to reproduce the temperature indicating [O III] λ4363/5007 line ratio. This failure is, in our opinion, a real challenge for the modelling of ionized gases and deserves particular attention in future works.

2. GIANT H II REGION MODELS AND THEIR UNCERTAINTIES

2.1. *Photoionization Codes*

The first step for evaluating the uncertainties involved in any modelling of a natural phenomenon is to intercompare similar codes that can be used for the modelling. As concerns photoionization, Péquignot (1986) and Ferland et al. (1995) have published the results obtained for several test cases by a dozen of photoionization codes. A number of codes agree rather well in their predictions, the agreement being generally worse for ultraviolet lines, whose intensities are strongly dependent on the computed electron temperatures. Part of the discrepancies may be attributed to the use of slightly different atomic data, although most of the codes had been updated from this point of view in probably a similar way. Differences in the numerical treatment of the

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transfer of radiation and in the description of the physical processes undoubtedly induce some scatter in the results obtained by various codes. Globally, the agreement between most of the photoionization codes is rather remarkable (note that the situation is much worse for shock codes, the shock models reported in Ferland et al. show serious discrepancies).

As emphasized by Ferland at this conference, atomic data computations have made enormous progress this last decade, both by the refinement of the techniques and by the volume of data produced. However, some of the atomic data used in photoionization models are still quite inaccurate, mostly as regards the third row elements. Charge exchange rates are uncertain even for the second row elements. Also, photoionization codes, so far, do not take into account the resonances that occur in the photoionization cross sections. For these reasons, the predictions from photoionization codes are less accurate than what may seem from an intercomparison of codes.

Some of the photoionization codes include the possibility of treating absorption of radiation by dust and heating and cooling of the gas by interactions of photons and gas particles with dust grains. However, the physics of dust grains is extremely complex, and the way in which dust is treated in photoionization codes is necessarily very simplified and probably inaccurate. Therefore, in any case where dust grains are suspected of being mixed with the ionized gas and playing a role either in the transfer of radiation or in the thermal balance of the gas, further uncertainties are expected, although these have not been quantified.

2.2. *Numerical Models for Real Nebulae*

In order to build a photoionization model, one needs to specify the intensity and spectral distribution of the ionizing radiation field, the chemical composition of the nebular gas and its density distribution.

For giant H II regions, it is generally supposed that the radiation field originates from a compact cluster of stars, and one simply adds up the radiation from the different stars composing the cluster (if the typical separation between the stars is an appreciable fraction of the size of the giant H II region, the validity of this assumption breaks down).

The radiation field is constructed using stellar population synthesis procedures that have been amply described in the literature. Stasińska (2000) gives a list of recent stellar population synthesis codes that have been applied to giant H II regions. The procedure for constructing a synthetic radiation field is the following. One considers a star cluster of given total initial mass and metallicity, given initial stellar mass function and given upper and lower mass limit, and one adopts a star formation law. Stars are binned into mass intervals. For each of them, stellar evolution models predict the stellar effective temperature and luminosity as a function of time. The radiation field for each mass interval is then represented by that of a model atmosphere adapted for the appropriate combination of metallicity, effective temperature and gravity. The total radiation field of the star cluster is obtained by adding up the contributions of the different stellar mass bins. Some of the models take into account the stochastic effects that affect the population of the most massive stars in star cluster of initial mass smaller than a few 10^5 $M_\odot$. Obviously, the radiation field predicted by such population synthesis techniques strongly depend on the adopted stellar evolution models and stellar atmosphere models. Some comparisons between various population synthesis models can be found in Charlot (1996) and Leitherer (1999).

Another problem is the geometry of the nebula. Most photoionization codes are constructed for simple geometries (plane parallel or spherical), in which the gas density can vary only along one dimension. Images of H II regions show that real nebulae are far more complex than that (see e.g., Esteban 2000 for a review). Inhomogeneities show up on every scale, and there is often no obvious symmetry characterising these objects. When comparing the emission line intensities predicted by photoionization models with those observed in H II regions, one must keep in mind that line ratios are affected by nebular geometry. An appropriate way of doing this with a code using spherical symmetry is to choose a model density distribution that is as compatible as possible with the one revealed by Hα images of the nebulae, and explore the effects of departure from spherical symmetry by means of numerical experiments.

Recently, a few three dimensional photoionization codes have been developped (Gruenwald, Viegas, & Broguière 1997; Och, Lucy, & Rosa 1998; see also Abel in these proceedings). Such codes would obviously find applications for giant H II regions. However, comparison of 3D models with nebulae that lack any kind of symmetry is likely to be very difficult, and appropriate methods must be worked out. In particular, even more than in the case of spherical objects, it is necessary to ask oneself what are the crucial line ratios to be reproduced and what is the tolerance one can accept.

3. THE ELECTRON TEMPERATURE PROBLEM IN GIANT H II REGIONS REVEALED BY MODEL FITTING

Detailed photoionization analysis has been undertaken for only a few giant H II regions. Three such experiments have been briefly reviewed by Stasińska (2000). In all of them, the [O III] λ4363/5007 ratio as returned by the models is significantly below the observed one. The three objects are: one nuclear giant H II region in the starburst galaxy NGC 7714, modelled by García-Vargas et al. (1997), one giant H II region in the irregular galaxy NGC 2363, modelled by Luridiana, Peimbert, & Leitherer (1999 and these proceedings) and one giant H II region in the metal-poor blue compact dwarf galaxy I Zw 18. The latter was modelled by Dufour, Garnett, & Shields (1988) and Campbell (1990) using single-star photoionization models, and then by Stasińska & Schaerer (1999) using an appropriate stellar population synthesis model. These objects differ by their masses and metallicities (from 0.4 $Z_\odot$ to 0.02 $Z_\odot$) but have in common the signature of Wolf-Rayet stars in their spectra. This provides strong constraints on the characteristics of the ionizing star clusters (age of the stars and masses of the most massive ones), reducing the number of free parameters in the modelling. Additional constraints come from the observed sizes of the ionized regions, the total nebular flux observed in Hα and, in the case of I Zw 18, the observed stellar UV flux.

As concerns I Zw 18, a real effort was made to reproduce the observed [O III] λ4363/5007 ratio. The first attempts invoked a mixture of individual H II regions with different ionization parameters or ionized by stars with various effective temperatures (Dufour et al. 1988) or a strong density enhancement towards the center (Campbell 1990). However, these explanations were invalidated by further observations (*HST* imaging and high signal-to-noise spectrocopy). Stasińska & Schaerer (1999) investigated further possibilities to explain the 30% discrepancy between the predicted and observed [O III] λ4363/5007 ratio in I Zw 18 (which, in terms of electron temperature, translates into a ΔT[OIII] of 3000K). They noted that the Hα profile obtained from *HST* images shows that the global geometry of the nebula is not that of a spherical bubble as might first appear, but is closer to a ring seen face on. In that case, photoionization models using spherical symmetry overestimate the role of the diffuse radiation field produced by the nebular gas, and thus underestimate the electron temperature. However, even assuming that all the ionizing field is as hard as the stellar radiation field would raise the predicted electron temperature by only 200 K. The spectral energy distribution of the stellar radiation field is actually quite uncertain, even when state of the art model atmospheres are used as is the case in Stasińska & Schaerer (1999). However, the level of uncertainty in the description of the stellar radiation field is not sufficient to account for the [O III] λ4363/5007 discrepancy: adopting an artificially hard radiation field (with a mean effective temperature $< T_{eff} >$ of the order of 100,000 K rather than 40,000 K) increases T[OIII] by 600 K only. Adding X-rays to the stellar radiation field does not improve the situation, since X-rays are absorbed in the outer parts of the nebula, not in the region emitting [O III]. Dust heating is certainly negligible in I Zw 18, since the metallicity is very low and thus the amount of matter that can condense into dust will build up a dust-to-gas mas ratios of at most a few 10^{-5}.

The only way out, in the framework of classical photoionization models, would be to assume that the collision strengths of the [O III] transitions could be off by about 30%.

4. THE ELECTRON TEMPERATURE PROBLEM IN ASTROPHYSICAL PLASMAS

The failure in reproducing the electron temperature in giant H II regions using classical photoionization models is significant. We are missing a non negligible fraction of the thermal energy in the nebular gas (about 20% in the case of I Zw 18), and of the heating power (a factor 2 in the case of I Zw 18).

This "electron temperature problem", or rather the fact that photoionization models produce an [O III] λ4363/5007 ratio smaller than observed, has also be noted in other astrophysical environments. For example, in some Seyfert galaxy nuclei (e.g., Stasińska 1984; Simpson et al. 1996), or in the extended emission line regions of active galaxies (Tadhunter, Robinson, & Morganti 1989; Binette, Wilson, & Storchi-Bergmann 1996) as well as in some planetary nebulae (Peña et al. 1998).

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So far, the case of I Zw 18 is the clearest of all. Indeed, many observational constraints are available that preclude explanations involving density enhancements or ad hoc density boundedness. Additional dust heating cannot be invoked either. In the case of active galaxies, for example, multi-density models or density-bounded models have been proposed to solve the discrepancy.

Shocks are commonly invoked to explain the high [O III] $\lambda4363/5007$ ratios, since they heat the compressed gas to very high temperatures. However, shocks are not very efficient at radiating. In the presence of a known source of ionizing photons, like in giant H II regions or planetary nebulae, shocks are likely to have very little effect on the overall emission spectrum. It should be noted, though, that an observational evidence of shock heating has be claimed by Dufour & Buckalew (1999) in one filament of the Wolf-Rayet shell nebula NGC 6888, where the [O III] $\lambda4363/5007$ ratio is interpreted as due to a temperature of 50,000 K. If this phenomenon were common, objects with a patent "temperature problem" should reveal such very high temperature zones if observed at high spatial resolution.

Another possibility to increase the [O III] $\lambda4363/5007$ ratio above the values predicted by classical photoionization models is conductive heating or turbulent mixing with a very hot gas, expected to be present inside stellar bubbles (Weaver et al. 1977).

Such processes must be investigated in more detail, especially in the context of giant H II regions, and modelled and confronted with observations without violating the constraints set by the ultraviolet emission lines.

This electron temperature problem may have something to do with the temperature fluctuations advocated by Peimbert (1967) (see also Peimbert 1995; Mathis 1995; Stasińska 1998). Based on indirect evidences, Peimbert argued that large temperature fluctuations exist in H II regions and planetary nebulae, so that the temperature derived from the [O III] $\lambda4363/5007$ line ratio is not representative of the average electron temperature in the O^{++} zone. However, no viable explanation for such fluctuations has been offered so far.

The electron temperature problem remains one of the main puzzles in nebular astrophysics. It is of concern to a wide community, not only because is deals with our understanding of the energy balance of photoionized gases, but because it has consequences on the abundances derived from emission line spectra.

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