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TEMPERATURE STRUCTURE AND CHEMICAL ABUNDANCES IN GASEOUS NEBULAE

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RESUMEN

Discuto algunos de los resultados presentados en este simposio sobre: nebulosas planetarias, regiones H II, evolución química de galaxias y la determinación de la abundancia primordial de helio. Para tener una visión más general de este simposio recomiendo leer todos los artículos incluidos en este volumen.

ABSTRACT

In this summary I review some of the results presented in this symposium relating to planetary nebulae, H II regions, chemical evolution of galaxies, and the determination of the primordial helium abundance. To get a more general perspective of this symposium I encourage you to read all the contributions to these proceedings.

Key Words: **EARLY UNIVERSE — GALAXIES: ABUNDANCES — H II REGIONS — ISM: ABUNDANCES — PLANETARY NEBULAE**

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1. OVERVIEW

To produce an accurate model of a gaseous nebula we should take its most relevant properties into account. These properties include: the geometry, the temperature structure, the density structure, the velocity structure, the dust content, the chemical abundances (together with possible chemical inhomogeneities inside a given object), and the energy sources.

Precise models of individual nebulae permit us to determine accurate abundances and the abundances allow us to test models of stellar evolution, Galactic chemical evolution, and the evolution of the Universe as a whole.

To have a good model of a given gaseous nebula a very good knowledge of the temperature structure is needed. The temperature structure is crucial for the determination of accurate chemical abundances. For the best observed objects usually we have a value of the average temperature T_0 and of the mean square temperature fluctuation, t^2. When t^2 agrees with the value predicted by chemically homogeneous photoionization models we are confident of the derived chemical abundances. Often the observed values of t^2 are higher than those predicted by the models and a source for the discrepancy should be sought. Two points should be made here: (a) the observational errors present in the t^2 determinations are high, but maybe lower than I expect because the overwhelming majority of the observational t^2 values present in the literature are positive, (b) as Daniel Péquignot mentioned during his talk t^2 is just an empirical parameter that should be adjusted by the model, a larger observational value for t^2 than that predicted by the model is only telling us that something is wrong with the model, but it is not telling us what is wrong nor which is the temperature structure. This review will be mainly centered on the relevance of the temperature structure in the determination of the chemical composition of different objects, another view of the role of the electron temperature in abundance determinations is presented by Stasińska (2001).

2. PLANETARY NEBULAE

The abundances derived from permitted lines run from similar to about an order of magnitude higher than those derived from forbidden lines (see the review by Liu 2001). By assuming that collisional deexcitation is not important (low density limit) and that the objects are chemically homogeneous it is possible to reach agreement between both types of determinations adopting a $t^2 > 0.00$.

The t^2 values determined from observations are in the 0.00 to 0.09 range, while those values predicted by chemically homogeneous photoionization models, CHPM, are in the 0.005 to 0.025 range. We can divide the well observed PNe in three groups: (a) those that have t^2 values smaller than 0.025, they can be fitted with CHPM and comprise about a third of the well studied cases, (b) those with intermediate t^2 values, in the 0.025 to 0.045 range, and (c) those with t^2 larger than 0.045, most of these objects are of Type I (Peimbert 1978; Peimbert et al. 1995) and show complex velocity fields reaching velocity differences of many hundreds of km s^{-1}, for these objects the deposition of mechanical energy might be significant. A lot of effort has been put into the determination of t^2 and special attention has been given to those objects with the largest t^2 values.

To explain the t^2 differences between the predicted values from CHPM and the observed values at least eight possible causes have been suggested in the literature (see the review by Esteban 2001): (a) large density variations, (b) chemical inhomogeneities, (c) deposition of mechanical energy due to shocks or dissipation of turbulent motions, (d) enhanced dielectronic recombination (Garnett & Dinerstein 2001), (e) shadowed regions ionized by indirect radiation from the nebula rather than direct radiation from the ionizing star (Mathis 1995), (f) magnetic reconnection (Ferland 2001), (g) observational errors, and (h) errors in the atomic parameters.

Some of these causes might be present in some objects and not in others. Only a careful analysis of a given object will indicate the relative importance of each of them.

One question that we want to answer is: which are the representative abundances for the whole nebula, those provided by the forbidden lines or those provided by the recombination lines? The answer is fundamental to constrain the evolution of intermediate mass stars and the chemical evolution of the Galaxy. If the effects due to (b) and (d) dominate then the representative abundances for the bulk of the mass ejected are those given by forbidden lines (see Liu et al. 2000; Liu 2001; Péquignot et al. 2001), alternatively if effects due to (a), (c), and (e) dominate then the representative abundances are those given by the permitted lines. Carigi (2001) has constructed models of the chemical evolution of the Galaxy based on observational yields of carbon derived from recombination lines and from forbidden lines of planetary nebulae, she finds that the models that use the yields based on permitted lines agree better with the observational constrains provided by H II regions and stars of the solar vicinity, than the models based on the yields derived from forbidden lines.

3. GALACTIC AND EXTRAGALACTIC H II REGIONS

There are two different problems related with the temperature structure of H II regions that are still controversial: (a) typical observed t^2 values are in the 0.01 to 0.04 range, while typical values predicted by CHPM's are in the 0.005 to 0.020 range. The differences in t^2 between CHPM's and observations of H II regions are smaller than in PNe but I think that they are real (see the review of Esteban 2001), and (b) in general photoionization models predict T(O III) values smaller than observed (Stasińska & Schaerer 1999; Luridiana, Peimbert, & Leitherer 1999; Luridiana & Peimbert 2001; Luridiana, Peimbert, & Peimbert 2001; Relaño, Peimbert, & Beckman 2001) indicating the possible presence of an additional heating source not considered by the models.

The warning mentioned by Viegas (2001) regarding point (b) above should be considered: models depend on many assumptions and a very good model is needed before we accept its implications. For example the difference between the observed and predicted T(O III) values depends on the adopted filling factor, ϵ; the difference between the observed and predicted T(O III) values for I Zw 18 disappears for models with values of $\epsilon > 0.3$.

4. CHEMICAL EVOLUTION OF GALAXIES

One of the controversial issues in the study of the chemical evolution of irregular galaxies is the low effective yield of oxygen derived from observations, one solution to this problem is to assume the presence of O-rich galactic outflows.

Several lines of reasoning indicate that O-rich outflows produced by gas rich irregular galaxies are unlikely. Larsen, Sommer-Larsen, & Pagel (2001) from chemical evolution models find that the N/O versus O/H relationship indicates that that O-rich outflows have not played an important role in nearby irregular galaxies (redshifts ~ 0). A similar result has been obtained by Carigi et al. (1995) and Carigi, Colín, & Peimbert (1999) based on the C/O versus O/H values for nearby irregular galaxies. Tenorio-Tagle (2001) from the mixing of metals argues that it is difficult to expel gas in dwarf irregulars with a low rate of star formation, moreover the mass lost would be of well mixed material; in this context Silich et al. (2001) analyze VII Zw 403, a metal poor irregular galaxy, and conclude that the heavy elements produced during the present starburst will not be ejected into the interstellar medium. One way to reduce the difference between the observed effective yield for oxygen and the yield predicted by models is the presence of dark matter (e.g., Carigi et al. 1999).

The N/O versus O/H relation has been studied by many authors (e.g., Garnett 1990, 2001; Pagel et al. 1992; Shields 2001; Skillman 2001; Larsen et al. 2001) there are some aspects of this relation that need further consideration.

The N/O ratio depends on the temperature adopted, especially for objects with low electron temperature, therefore the errors in the N/O determina-

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$$\begin{aligned}\frac{N(\mathrm{He})}{N(\mathrm{H})} &= \frac{\int N_e N(\mathrm{He}^0)dV + \int N_e N(\mathrm{He}^+)dV + \int N_e N(\mathrm{He}^{++})dV}{\int N_e N(\mathrm{H}^0)dV + \int N_e N(\mathrm{H}^+)dV}, \\ &= ICF(\mathrm{He})\frac{\int N_e N(\mathrm{He}^+)dV + \int N_e N(\mathrm{He}^{++})dV}{\int N_e N(\mathrm{H}^+)dV}. \qquad (1)\end{aligned}$$

tions might be larger for objects with lower temperatures. To determine the N/O ratio often the temperature derived from the $\lambda\lambda\,4363/5007$ ratio, T(O III), is used as representative of the O^+ and N^+ zones; from photoionization models it is found that for objects with T(O III) $> 12\,360$ K, the temperature of the O^{++} region is higher than the temperature of the O^+ region, the opposite is found for objects with T(O III) $< 12\,360$ K (e.g., Stasińska 1990); if this effect is not taken into account the N/O value for metal rich H II regions (those with T(O III) $< 12\,360$ K) will be underestimated while for metal poor H II regions (those with T(O III) > 12360 K) N/O will be overestimated.

Often it is assumed that the N/O ratio is equal to the N^+/O^+ ratio (assuming that the O^+ zone coincides with the N^+ one), while some photoionization models indicate that this is the case, others indicate that it is at best a fair approximation (Relaño et al. 2001).

Apparently there are environmental effects present in the N/O versus O/H relation, while Peimbert & Torres-Peimbert (1992) find an underabundance of the N/O ratio for a given O/H ratio in the Boötes Void galaxies, Vílchez & Iglesias-Páramo (2001) find that there is an overabundance of N/O for a given O/H in the dwarf galaxies of the Virgo cluster.

5. PRIMORDIAL HELIUM ABUNDANCE

The determination of the pregalactic, or primordial, helium abundance by mass $Y_{\rm p}$ is paramount for the study of cosmology, the physics of elementary particles, and the chemical evolution of galaxies (e.g., Boesgaard & Steigman 1985; Fields & Olive 1998; Izotov et al. 1999; Peimbert & Torres-Peimbert 1999; Olive & Skillman 2000 and references therein).

We will call $Y_{\rm p}$(nHc) those $Y_{\rm p}$ values in the literature derived under the assumption of no contribution to the hydrogen Balmer lines due to collisional excitation.

The best determinations of $Y_{\rm p}$(nHc) in the literature are those of Izotov & Thuan (1998); Izotov et al. (1999); and Peimbert, Peimbert, & Ruiz (2000) that amount to 0.2443 ± 0.0015, 0.2452 ± 0.0015, and 0.2345 ± 0.0026, respectively. These determinations are based on 45, 2, and 1 extragalactic H II regions, respectively, and the differences between the first two and the last one amount to at least 3σ.

To study the source of this discrepancy Peimbert & Peimbert (2001) and Peimbert, Peimbert, & Luridiana (2001) decided to compute $Y_{\rm p}$(nHc) based on the data by Izotov & Thuan (1998) and Izotov et al. (1999). From two different subsamples of the best observed objects, comprising 12 and 5 objects, found that $Y_{\rm p}$(nHc) amounts to 0.2371 ± 0.0015 and 0.2360 ± 0.0025, respectively. These results are in good agreement with the value derived by Peimbert et al. (2000) and are significantly smaller than the values derived by Izotov & Thuan (1998) and Izotov et al. (1999).

The main source of the discrepancy between both groups of authors is due to the treatment of the temperature structure inside the nebulae; while Izotov & Thuan (1998) and Izotov et al. (1999) adopt T(O III) to derive the helium abundance, Peimbert & Peimbert (2001) and Peimbert et al. (2001) from the He I line intensities and adopting $t^2 > 0.00$ determine T(He II) values 6–11% smaller than T(O III). In the self-consistent solutions the smaller T(He II) values imply higher densities; the higher the density the higher the collisional contribution to the He I line intensities and, consequently, the lower the helium abundances.

The baryon energy density, $\Omega_{\rm b}$, values derived by Peimbert & Peimbert (2001) and Peimbert et al. (2001) from the $Y_{\rm p}$(nHc) values are significantly smaller than the $\Omega_{\rm b}$ value derived from the $D_{\rm p}$ determination by O'Meara et al. (2001). Before we conclude that a non-standard big bang nucleosynthesis model is needed to reconcile the differences it is necessary to analyze further two possible systematic effects: (a) the ionization structure of the H II regions, and (b) the collisional excitation of the hydrogen lines.

To determine very accurate He/H values of a given H II region we need to consider its ionization structure. The total He/H value is given by equation (1) above.

For objects of low degree of ionization it is necessary to consider the presence of He^0 inside the H^+ zone, while for objects of high degree of ionization it is necessary to consider the possible presence of H^0

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inside the He^+ zone. For objects of low degree of ionization *ICF*(He) might be larger than 1.00, while for objects of high degree of ionization *ICF*(He) might be smaller than 1.00. The deviations from unity in the *ICF*(He) value occur in and near the ionization boundary of a given H II region, therefore those H II regions that are density bounded in all directions have an *ICF*(He) = 1.00. The *ICF*(He) problem has been discussed by many authors (e.g., Shields 1974; Stasińska 1983; Peña 1986; Vílchez & Pagel 1988; Pagel et al. 1992; Armour et al. 1999; Peimbert & Peimbert 2000; Viegas, Gruenwald, & Steigman 2000; Viegas & Gruenwald 2000; Ballantyne, Ferland, & Martin 2000; Sauer & Jedamzik 2001).

Based on models of metal poor H II regions Luridiana et al. (2001) find that the *ICF*(He) for some of the best observed objects is very close to 1.00 and consequently that the main difference between the Ω_b value derived from Y_p(nHc) and D_p is not due to the *ICF*(He). Relaño et al. (2001) from the spectral types of the ionizing stars of NGC 346 find that about half of the ionizing photons escape the nebula favoring an *ICF*(He) = 1.00, this result is also supported by the fit of the lines of low degree of ionization by their photoionization model. From the work by Zurita, Rozas, & Beckman (2000) on the ionization of the diffuse interstellar medium in external galaxies it is expected that a large fraction of the ionizing photons escapes from the most luminous H II regions, which favors the assumption that the *ICF*(He) is very close to 1.00.

Davidson & Kinman (1985) were the first to estimate the collisional contribution to the Balmer lines and its effect on the determination of Y_p; they made a crude estimate for I Zw 18 and concluded that the collisional contribution to $I(H\alpha)$ *may* be roughly 2%. All the subsequent determinations of Y_p in the literature have been derived under the assumption of no contribution to the hydrogen Balmer lines due to collisional excitation, I have referred to these determinations in this paper as Y_p(nHc).

Notice that to a very good approximation the collisional excitation of the Balmer lines does not affect the maximum likelihood method determinations of N_e(He II), T(He II) $\tau(3889)$, and T(O III).

From a series of Cloudy models it is found that the collisional contribution to $I(H\beta)$ for I Zw 18 and SBS 0335-052 is in the 2% to 6% range, for H 29 and NGC 2363 in the 1% to 2% range, and for NGC 346 in the 0.6% to 1.2% range. Our preliminary results indicate that the primordial helium abundance including hydrogen collisions, Y_p(+Hc), is about 0.0050 larger than Y_p(nHc). This problem together with the Cloudy models for I Zw 18, SBS 0335-052, and H 29 will be discussed elsewhere Luridiana et al. (2001). The Cloudy models for NGC 2363 and NGC 346 are those by Luridiana et al. (1999) and Relaño et al. (2001), respectively.

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