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THE DIFFUSE IONIZED GAS IN THE LARGE TELESCOPES ERA

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RESUMEN

En este taller asociado al congreso general intentamos resumir el estado en el que se encuentra el estudio del Gas Ionizado Difuso (DIG). Presentamos todas las posibles formas de ionizar el gas fuera de regiones H II así como algunas de las observaciones que se podrán realizar con la instrumentación de primera luz en el GTC. También estudiamos cómo de relevante sería la misma para poder entender cuál es el mecanismo que está produciendo esta ionización en el DIG.

ABSTRACT

In this workshop we summarize the "state of the art" of the Diffuse Ionized Gas. We present all the possible situations which can produce ionization outside an H II region, as well as some of the observations that can be performed with the GTC instrumentation and how relevant they can be in the undestanding of the ionization mechanisms of the DIG.

Key Words: **GALAXIES: INTERGALACTIC MEDIUM — GALAXIES: ISM**

1. INTRODUCTION

The existence of a layer of diffuse ionized gas (hereafter, DIG) above the galactic plane in the Milky Way, called the Reynolds layer, is nowadays very well known. Similar layers have been found in several galaxies. In some of them this ionized gas is found up to 3 kpc from the galactic plane. The properties are very similar in all the galaxies: very low densities ($\approx 10^{-3}$ cm^{-3}) as well as low excitation ([OIII]/Hβ ≈ 0.17, both values for the Milky Way (Reynolds, 1983)). Also, high ratios of both [NII]/Hα and [SII]/Hα can characterize the DIG.

A diffuse gas with low ionization is observed among H II regions in irregular galaxies as well. Here, the properties are slightly different: the ionization and excitation are higher than observed in DIG in spiral galaxies but with lower values than in H II regions. On the contrary, the [NII]/Hα and [SII]/Hα ratios have lower values than in spirals but larger than inside H II regions (Hidalgo-Gámez 2004). Differences in metallicity between spiral and irregular galaxies, as well as the different sizes in the OB associations can account for these differences in the line ratios.

The best parameter for a definition of DIG is the emission measure (EM), which is related with the density through

$$EM = \int_l N_e \; N_i \; dl$$

(see Torres-Peimbert et al. 1974), where N_e is electron density and N_i is the ion density, both in cm^{-3} and l is in parsec. In terms of the electronic temperature and the surface brightness in the Hα line it can be read as

$$EM = 7.2 \; 10^{13} \; SB(H\alpha) \; T^{0.9}$$

where $SB(H\alpha)$ is in erg cm^{-2} s^{-1} arcsec^{-2}. Typically, H II regions, with densities of 100 cm^{-3}, have EM of 50 or larger while values as low as 4 are expected for regions with densities of 0.1 cm^{-3}. Emission .,measures of 2 or lower are found in the DIG in the Milky Way and in other galaxies (e.g. Haffner, Reynolds, Tufte et al. 2003; Hidalgo-Gámez, Richer, Georgiev & Bullejos in preparation).

The main problem in the study of the diffuse ionized gas is to understand the source of ionization. This is specially important when gas at very high altitudes is considered. Moreover, the key question is: **How many sources are ionizing the DIG?** Several models have been proposed in order to explain all the characteristics observed but, so far, none of the models can account for all of them in all the galaxies. In the following, we will describe all the possible mechanisms which might produce the observed line ratios.

2. WHAT IS IONIZING THE DIFFUSE GAS?

For more than twenty years several models have been proposed in order to explain the degree of ionization as well as the high values of the [NII]/Hα and [SII]/Hα ratios in the Diffuse Ionized Gas. Standard photoionization from OB stars, escape of photons

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from H II regions, shocks or turbulent mixing layers are some of the most common explanations but some others like errand OB stars, hot stars (e.g Wolf-Rayet or nuclei of planetary nebulae), X-rays, cosmic rays or scattered light might also play a role. In order to discriminate among them it is important to know if they can ionize the gas. Domgörgen & Mathis (1994) obtained that in order to ionize the DIG in the Milky Way only 15% of the power of O stars ionizing radiation is needed. Considering the Salpeter IMF and the differences in the ionizing flux for each type of O stars, a total ionizing flux of $\approx 10^{43}$ erg s^{-1} is determined for the O stars population of the Milky Way ($\approx 10^4$). Whatever the model used to explain the degree of ionization it must produce at least 1.6 10^{42} erg s^{-1} at the distance the DIG is located.

2.1. *Photoionization*

Mathis (1986) tried to fit the observed properties of the Milky Way DIG with ionization by OB stars. He considered in his model an exponential variation of the electron density with distance from the galactic plane. One of the results he obtained was that the q parameter, which is the ratio between the ionizing photon density and the electron density, has lower values, at least a factor of 10^2, for DIG models than for H II regions models. Moreover, there was a lack of dependence of the line ratios on the stellar temperature. As a consequence, a composite model where stars with different temperatures are considered, was performed. In oder to fit the ionization and excitation q must be 0.001, while at least values of $q = 10^{-5}$ are needed for the [NII]/Hα and [SII]/Hα ratios.

The main difficulty is the low number of observed quantities which could be compared with the model at the time Mathis's paper was published. Few years later other important line ratios like [OII]/Hβ, [OI]/Hβ and HeI/Hβ, were observed in some directions in the Milky Way (Reynolds et al. 1998; Tufte 1997) and therefore a better determination of the model parameters could be obtained.

New photoionization models have been computed recently (e.g. Domgörgen & Mathis 1994) focussing again on the Milky Way. A composite model with $log\ q = -4$ fits more or less all the line ratios in the Galaxy, but except M31 no other galaxy can be fitted with a single model and a single value of q. Moreover, for none of the other external galaxies the line ratios can be explained with any value of q. Therefore, a single simple photoionization model cannot explain the ionization level of the DIG in all the galaxies.

Other situations can be invoked. The H II regions may not trap all the photons produced by the massive stars so part of them will escape into the Interstellar Medium. Moreover, OB stars themselves can escape from H II regions and ionize "in situ" the diffuse gas. Finally, other hot stars like Wolf-Rayets or nuclei of planetary nebulae, which are not located inside H II regions, can produce the ionization levels observed for DIG.

Recently, Relaño et al. (2002) concluded that 45% of the photons produced by the ionizing stars in NGC 346 escape from the H II region. This result, they claimed, is independent of the geometry of the region. This is in agreement with the results by Hoopes & Walterbos (2003). They concluded that standard photoionization models cannot reproduce the observable line ratios in DIG. Leaky H II regions with an escaping of photons ranging between 30% and 70% can reproduce the excitation better. According to Relaño et al. (2002), the total flux of NGC 346 is 31.28 10^{39} erg s^{-1}, and the flux which escapes is of 14 10^{39} erg s^{-1}. Those models probably depend on the density and the ionization level of the DIG; NGC 346, in the SMC, might have a lower ionization level by 10-100 times that the DIG in the Milky Way and therefore the ionizing photons that escape from H II regions can produce the ionization level observed. The same cannot be true for other H II regions and other galaxies.

The main caveat with leaky models is how far can a photon travel. This distance is related with the total gas density of the galaxy as well as with the density distribution inside the galaxy. If the density is high, the photons will be trapped in the neighbourhood of the H II regions so they do not travel far from them. On the contrary, low density regions will allow photons to travel large distances. If their trajectory is perpendicular to the disc, as the density drops down exponentially (Mathis 1986), the distance will be larger than for photons travelling through the disc. The situation is more interesting if the density is not uniform inside the galaxy (see Beckman's contribution in this volumen). In this case, the distances travelled by the photons vary for different directions and the ionization level in the Reynolds layer may not be homogeneous (uniform).

In a study of the ionization level of the interarm region of M33, Benvenuti et al. (1976) concluded that OB stars located in these interarm regions can be responsible for the ionization level. It is known (Cruz-Gonzalez, Recillas-Cruz, Costero et al. 1974) that half of the O stars in the Galaxy are not inside H II regions but in locations with an emission measure smaller than 50, especially O7 and later types. There are two possibilities: firstly, these stars have escaped from the H II regions where they were born. Cruz-Gonzalez et al. (1974) detected that older stars tend to drift out of the plane. They were located 100 pc over the galactic plane. Such distance is very small as compared with 3 kpc to where the DIG has been detected. But, "runaway" O stars must be taken into account when diffuse gas at the plane level is considered. The second possibility is that there are "fossil" H II regions. It means H II regions which are old enough as not to have OB stars inside, but the gas is still ionized. The recombination time depends on the density as $t_{rec} = 10^5/Ne$ yr and for regions with a density of ≈ 0.1 cm^{-3} it takes the gas about 10^6 years to recombine. Therefore, when O stars disappear the gas continues ionized a long time enough to be detected.

Not only OB stars can produce ionization; other hot stars can be important in the ionization of the diffuse gas as well. Each Wolf-Rayet star produces a Strömgren sphere larger than 125 pcs and a flux of $7\ 10^{39}$ erg s^{-1}. In spite of these large values and due to their short life time ($\approx 10^5$ yr), these stars can produce at most 10% of the ionizing photons needed for the DIG ionization level. Another problem is that not all the galaxies have this kind of stars. But, there are galaxies which hold a large population of such stars, so called Wolf-Rayet galaxies, for which these stars might represent an important source of ionization. An example is the local dwarf IC 10, with at least 27 WR stars for an optical size of 760 pcs (Crowther, Drissen, Abbott et al. 2003). In a recent study of the DIG properties of this galaxy (Hidalgo-Gámez et al. in preparation) it was found that while the [NII]/Hα and [SII]/Hα ratios for the DIG are lower than in spiral galaxies, the excitation is very large. None of the models can explain such a high excitation without considering the WR stars as an extra source of excitation of the interstellar medium.

Nuclei of planetary nebulae are also very hot stars. The younger ones can have temperatures of $100,000$ K (Kaler 1989). On the other hand, they tend to be alone, while OB stars are in large associations, therefore the total ionizing power can be larger for the latter. Favouring these stars as ionization source is the large number of this type of stars, a total of $2,000$ known in the Milky Way (Acker, Ochsenbein, Stelholm et al. 1992) but there are estimations that the total number could be up to $20,000$ (Kwok 2000). Moreover, they are typically located at high altitudes ($< z > \approx 300$ pc) over the galactic plane. The main problem is that the fraction of ionizing photons that escapes to ionized the DIG is relatively small because the surrounding planetary nebula envelope is optically thick to the ionizing radiation most of the time. Therefore, the total number of ionizing photons that can be useful is smaller than for OB and WR stars.

2.2. *Shocks*

One of the most intriguing characteristic in the DIG line ratios is the large values of [SII]/Hα (and also [NII]/Hα). This ratio is normally related with shocks (Dopita 1976) and was widely used in diagnostic diagrams to separate shocked objects (SN, AGN, etc) from thermal objects (H II regions). Therefore, the existence of shocked gas at DIG (or a phase of shocked gas) has been one of the most common explanations. One caveat is that this ratio is metallicity dependent (Dopita & Sutherland 1993). Favouring this hypothesis is the behaviour of the [NII]/[SII] ratio, which cannot be explained by photoionization (Rand 1998). One problem is that shocks will enhance other line ratios, like [OI]λ6300 Å. This is a troublesome line because it has a galactic component as well as an extragalactic part. Therefore, at medium resolution these two components cannot be disentangled properly for nearby galaxies. Despite the lack of conclusive data, this line is not as intense (when detected) as the models predict. Moreover, the low speed shocks which are favoured in all the models because they are produced easily, will result in large [OIII]/Hβ ratios (Dopita & Sutherland 1993), while decreasing for larger velocities. On the contrary, high velocity shocks are needed in order to produce [NII]/H$\alpha > 0.5$ (Binette et al. 1985). Rand (1998) concluded that [NII]/Hα and [SII]/Hα on one hand and [OIII]/Hβ on the other arise from different phases in the DIG

Despite that shock models alone cannot explain all the line ratios, a shocked component in the diffuse gas is favoured when the kinematics of the DIG is considered. Wang et al. (1997) found broad lines in [OIII]λ5007 Å in a sample of spiral galaxies, Tüllman & Dettmar (2000) found a broadening of the lines with z for several galaxies and Valdez-Gutiérrez, Rosado, Puerari et al. (2002) found abrupt velocity gradients and supersonic velocity dispersions in the DIG of the irregular galaxy NGC 4449. Therefore, it can be concluded that there is a disturbed component of the DIG.

Nevertheless, most of the authors do not consider shocks but as a secondary source of ionization of the DIG. Actually, Collins & Rand (2001) used a composite model (photoionization + shocks) in order to explain the line ratios of NGC 4302 and UGC 10288.

In any case, the main problem is the mechanics which produces those shocks. Martin (1997) said that winds from OB associations can create bubbles and that their interaction with the interstellar medium will produce shock waves strong enough to be detected. A caveat is that these bubbles are created only in the neighbourhood of giant H II regions, localized in the galactic planes. No bubbles have been detected so far in not starbursting galaxies. Probably they are there but cannot produce shock waves strong enough to be detected. In this situation it is very difficult that such shocks would have such a strong influence on the DIG and particularly at very large z.

2.3. *Turbulent mixing layers*

Turbulent mixing layers offer another possibility for obtaining the spectral characteristics of the DIG. In this case, hot and cold (or warm) gas will be mixed in the interface of their layers due to Kelvin-Helmholtz instabilities (Begelman & Fabian 1990). As a result, the emitting gas would have enhanced [SII]/Hα and [NII]/Hα, [OIII]/Hβ > 1 and low [OI]/Hα, as observed. Such a situation is also favoured by the complex kinematics of the DIG. The weak point is, again, the [NII]/[SII] ratio, which cannot be reproduced properly.

Turbulent mixing layers cannot acount for all the emission of the DIG, not even at high z where the situation is most favourable due to the breaking of the superbubbles created by this instability. Slavin et al. (1993) considered that only 10% of the ionizing Hα emission in the DIG in the Milky Way is due to this mechanism. In irregular and active galaxies it could account for a larger percentage, but it is considered always as a secondary source.

2.4. *Other mechanisms*

Despite that the mechanisms described so far are the most often applied in order to explain the ionization of the diffuse gas, some others should be considered. The main reason is that not all the galaxies can be explained with only one model, not even with photoionization and a secondary source. There are many examples where a third source is needed (e.g. NGC 891, Rand 1998; Hidalgo-Gámez et al. in preparation).

Magnetic reconnection (Raymond 1992) can heat the halo and will produce ultraviolet emission, soft X-rays and a broad range of [OIII]/Hα values.

Dissipation of turbulent energy (Minter & Balser 1997) can raise the temperature of the ISM without increasing the ionized He, as observed.

Photoionization by EUV or X-ray sources can be important in those galaxies where such sources are present (e.g. NGC 3079, Veilleux et al. 1995).

Energetic cosmic rays can ionized He^+ to He^{++}, therefore the large HeIIλ4686/Hβ ratio might be explained.

Finally, another possibility is that we are observing scattered light. An example is the Orion nebula. Ionized elements (H^+, O^+, O^{++} etc) are observed as far as 24 arcminutes from the centre of the nebula. In order to explain the ionization level at such distance strong variations in the filling factors with the distance are needed (e.g. Simpson 1973). On the other hand, if the nebula radius is only 12 arcminutes, a model with a constant filling factor can explain the mayority of the characteristics (Peimbert 1982). Considering the large amount of dust in the nebula (McCall 1981), it can be concluded that the lines observed at large distances are due to scattered light. Moreover, all these lines are polarized and therefore there is no gas emitting there. This is an interesting possibility for dusty spiral galaxies which have ionized gas at large z.

3. THE DIG WITH THE GTC

Most of the investigations carried out so far were performed with small size telescopes. The main reason given to deny large-size telescope time is that the surface brightness does not depend on the telescope size and low EM's can be reached with small-size telescopes. Nevertheless in addition to be able to detect regions with low EM, high spectral and spatial resolution are needed in order to solve the problem of the ionization in the DIG. The first one will help in the resolution of some of the lines, like [OI]λ6300 Å or HeIλ5875 Å, while the second one is needed in order to disentangle DIG emission and H II emission in non-local galaxies. Moreover, there are some lines which might bring some light into this subject which have not been detected with enough S/N or simply not detected so far. The integration times needed to do it on a small-medium size telescope are beyond the scope of any observing program.

One of the most interesting elements is Helium. The spectral lines of the He^o can be produced mainly by recombination. Therefore, the intensity of them might permit to estimate the contribution of photoionization to the DIG. The main problem is that the stronger line, HeIλ5875 Å, is close to the Na sky line and with medium resolution spectra they cannot be disentangled. Another strong line, HeIλ4471 Å, might be affected by underlying absorption. Moreover, HeIλ6678 Å is 3 times weaker than HeIλ5875 Å so it is not detected yet in the DIG. With OSIRIS low-medium resolution grisms and the GTC collective area this line would be detected if present in the DIG. If the line is absent, an upper limit to the photoionization contribution can be given. Another interesting line is HeIIλ4686 Å. As mentioned before, cosmic rays can ionized He^+ to He^{++}. Therefore, if the line is absent it can be concluded that the influence of the cosmic rays in the ionization of the DIG is negligible. In addition, observations of galaxies with different Star Formation Rates will need to be performed because when the SFR is larger, more photons can escape from the H II regions boundaries. Therefore, the ionization level might differ with the Star Formation Rate.

OSIRIS can be very useful in the detection of DIG in external galaxies due to the large field of view (8' × 8'). Tunable filters will give the opportunity of observing at the Hα line and the continuum at the same time and, therefore, to detect this diffuse gas in external galaxies. Finally, OSIRIS will help also in the detection of shock waves. The high resolution grism ($\approx$ 5000) will provide the resolution needed for obtaining the velocity fields.

Another explanation that can be checked with the instrumentation of the GTC consists in the observations of scattered light. Its main property is the polarization. This can be measured when the polarimeter will be installed at OSIRIS or with the polarimeter in the medium infrared at Canaricam. Moreover, Canaricam will provide images in the medium IR and therefore the dust content can be checked out. These two types of observations can be used to rule out the hypothesis of scattered light by dust.

All these observations can be complemented with far infrared data as well as X-ray data. The first one can give information on the warm dust content while the X-ray can be useful in the detection of bubbles from OB winds or Kelvin-Helmholtz instability. Wherever the bubbles are, they should be detected at this wavelength.

4. CONCLUSIONS

Our main interest during this workshop was to study the different explanations used so far to explain the line ratios observed in DIG and how successful was each one of them. Our interest was twofold: we wanted to know which information was available in order to do some modelling. On the other hand, we were interested in which information could be obtained with the instrumentation at the GTC and how useful it would be in understanding the ionizing mechanisms of DIG.

This is a summary of those points: we outlined the most important explanations of the ionized diffuse gas as well as their main problems. None of them is completely satisfactory. Moreover, none can explain the DIG in all the galaxies.

There is much work to be done. Not only improvements in the models but also more data on a broad range of galaxies (irregulars, starburst, WR galaxies, etc) are needed. Also, deeper observations are interesting in order to detect weak lines, like [OI], [NI], HeI, which can be of utter importance in the determination of the contribution of photoionization or shocks in the DIG.

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