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Astrophysical Plasmas: Codes, Models, and Observations (Mexico City, 25-29 October 1999)
Editors: Jane Arthur, Nancy Brickhouse, & José Franco

EXCITATION OF THE DIFFUSE IONIZED GAS IN GALAXIES

Crystal L. Martin

Caltech, Pasadena, CA, USA

RESUMEN

Se revisan las propiedades del gas ionizado difuso (DIG) en galaxias cercanas con formación estelar, enfatizando la evidencia para un mecanismo de excitación adicional a la fotoionización estelar. Discuto la pregunta frecuentemente hecha sobre si el DIG en galaxias externas es similar al medio ionizado tibio (WIM) descrito en esta reunión por Reynolds y Haffner.

ABSTRACT

I review the properties of the diffuse ionized gas (DIG) in nearby star-forming galaxies emphasizing the evidence for a secondary excitation mechanism in addition to stellar photoionization. I address the frequently asked question of whether the diffuse ionized gas (DIG) in external galaxies is a good analogy to the warm ionized medium (WIM) described by Reynolds and Haffner at this meeting.

Key Words: **GALAXIES: ISM — GALAXIES: STARBURST**

1. BACKGROUND

Warm ionized gas is a prominent component of the interstellar medium in many galaxies with active regions of star formation (Dettmar 1992). In external galaxies, this phase is often called the DIG, for diffuse ionized gas (Rand 1996), while the name warm ionized medium (WIM) generally refers to gas in the Milky Way (Reynolds 1991). Different, yet similar, names have been used to describe the warm gas because it is not always clear whether a close analogy with the Galactic WIM is warranted (the name DIM, for diffuse ionized medium, is also in use for external galaxies).

My presentation summarizes results from longslit spectroscopy of nearby galaxies. Details about a large sample of dwarf galaxies can be found in Martin (1997) and Martin & Kennicutt (1997). Rand (1996) reviews the results for the halos of edge-on spiral galaxies. Papers by Wang, Heckman, & Lehnert (1997) and Greenawalt et al. (1998) provide many examples of DIG in galaxies seen nearly face-on. Following the requests of many conference participants, I reproduce here the quiz that followed my short review. The answers provide a good summary of the talk.

2. ANSWERS TO SOME KEY QUESTIONS

I. The transition between H II Regions and the DIG is . . .
(a) Defined by a critical Hα surface brightness.
(b) Defined by a [S II]/Hα intensity ration of 0.5.
(c) Smooth and continuous in terms of spectral signature and surface brightness.
(d) Both a and b.

Answer: The best choice is *c*. A good definition of where an H II region ends and the DIG starts is not a well-posed question. Figure 3 in Martin (1997) illustrates the gradual increase in the [S II]/Hα line ratio with declining Hα surface brightness across eight dwarf galaxies. Along this transition sequence from H II regions into the DIG, the forbidden lines from other low ionization states of common elements also increase in strength relative to the Balmer lines (e.g., Fig. 4 in Martin 1997).

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A universal definition of the distinction between H II regions and DIG seems to require some type of normalization based on the galactic star formation rate. Wang et al. (1998) suggest, for example, that the ratio of the Hα surface brightness relative to the mean Hα surface brightness of the galaxy provides a consistent prediction of the absolute [S II]/Hα ratio.

II. Relative to H II regions, the spectrum of the WIM in the dwarf galaxies shown ...
(a) Shows stronger lines of low ionization species.
(b) Exhibits a similar ratio of (He+/He) / (H+/H).
(c) Has weaker [O III] λ5007 emission relative to the Hβ emission.
(d) All of the above.

Answer: The best choice is *d*. The answer to Question 1 indicates that (a) is true. In contrast, the He I λ5876 / Hα ratio shows little variation with surface brightness. In many of the starbursting dwarf galaxies the reddening corrected ratio of He I λ5876 / Hα is near 0.041 (Martin & Kennicutt 1997) . The implied high ionization fraction of He leads us to conclude that stars hotter than 40,000 K must contribute to the ionizing continuum that reaches the DIG. One important difference with the WIM is that the He ionization fraction is lower in the WIM (Reynolds & Tufte 1995).

III. Why are the H II regions in NGC 1569, NGC 4214, and NGC 4449 offset along the H II region excitation sequence?
(a) Their chemical abundances differ.
(b) The effective temperature of their ionizing stellar population differs.
(c) The ionizing luminosities are quite different.
(d) The warm ionized clouds have different volume filling factors in these H II regions.

Answer: The best choice is *d*. Abundance variations do contribute to the offsets among galaxies in Figures 3 and 4 of Martin (1997). However, the three galaxies listed in the question were carefully chosed to have a very similar O/H abundance ratio. All three have very young stellar populations, and their extinction corrected Hα luminosities are similar (Martin & Kennicutt 1997). Comparison of the H II region electron densities to their root-mean-square electron densities reveals significant differences in the volume filling factor of the warm ionized gas (Martin 1997).

IV. Shocks are a likely secondary source of ionization and heating because ...
(a) The line ratios diverge from those predicted by photoionization models at low surface brightness.
(b) Large-scale expanding shells have been detected kinematically.
(c) They explain the differences in the [O III]/Hβ intensity ratio among dwarf galaxies and more luminous galaxies.
(d) All of the above.

Answer: The best choice is *d*. Figure 9 of Martin (1997) shows the divergence of the line ratios from the photoionization tracks. Shocks with a velocity of 90 km s^{-1} are introduced as a plausible secondary excitation mechanism there. The discovery of kiloparsec-scale gas flows at a similar velocity makes this interpretation the favored one (Martin 1998). Higher shock speeds and higher metallicities in more luminous starbursts provide a simple explanation for the changes in the line intensity ratio of [O III]/Hβ. Figure 10 of Martin (1997) shows that this model also successfully explain the increase in the [O III]/Hβ ratio with declining Hα surface brightness in the halo/wind of M82.

V. The main difference between the DIG in these galaxies and the WIM in the Milky Way is ...
(a) The strong low ionization state lines in the former.
(b) Higher He I λ5876 / Hα intensity ratio in the former.
(c) The need for a secondary excitation mechanism.
(d) The higher emission measure of the warm gas observed in dwarf galaxies.

Answer: The best choice is again *d*. The low ionization state lines are stronger in the WIM as well as the DIG, so answer (a) is a poor choice. Answer (b) is true, but the significance of this difference is currently unclear. It might only reflect a softer ionizing spectrum in the Milky Way. In addition to stellar photoionzation, a second source of excitation and/or heating is required to explain the line ratios of DIG in starbursting dwarf galaxies, DIG in edge-on spiral galaxies (Rand 1998), and the WIM (Reynolds, Haffner, & Tufte 1999; Haffner, Reynolds, & Tufte 1999). A potential source of confusion is that the mechanism need not be the same in all these galaxies. Shocks can dominate in the starbursting galaxies even if photoelectric heating or turbulent dissipation dominates in the WIM. The key point, as stated in answer (d), is that the observations of the WIM by the Wisconsin Hα Mapper reach much lower emission lines, EM $\equiv \int n_e^2 ds$, than the DIG observations have yet explored. This difference is very important since many of the proposed secondary heating mechanisms would be relatively more important at lower densities.

3. CONCLUSIONS

These questions and answers clarify some common misconceptions about DIG in galaxies. Clearly, there is a good reason to compare the DIG with the WIM! The properties of both the DIG and WIM tell us a great deal about the physical processes that transfer energy from stars to the interstellar medium. However, the differences in surface brightness should be kept in mind when making comparisons between the WIM and warm gas in other galaxies.

I wish to thank the conference organizers for an excellent meeting.

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Crystal L. Martin: Caltech, Pasadena, CA 91125, USA (clm@astro.caltech.edu).

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