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HII radiative transfer revealed by ionization parameter mapping

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Abstract. We develop the technique of ionization parameter mapping (IPM) to probe the optical depth of HII regions, applying our method to the Magellanic Clouds. Our results dramatically clarify the radiative transfer in these galaxies. Based on [SII], [OIII], and Hα imaging from the Magellanic Clouds Emission Line Survey, we find that the frequency of optically thin objects correlates strongly with Hα luminosity and correlates inversely with HI column density. The aggregate escape fraction for the Lyman continuum is sufficient to ionize the diffuse, warm ionized medium, but the galactic escape fraction is dominated by the few largest HII regions. The quantitative trends are similar in both the LMC and SMC in spite of their different star formation and HI properties.

Keywords. radiative transfer, stars: early-type, HII regions, galaxies: ISM

1. Introduction

The diffuse, warm ionized medium (WIM) is the dominant component of ionized gas in the interstellar medium (ISM). While its existence has been known for decades, we still lack a quantitative understanding of its origin. The WIM comprises about 60% of the total Hα luminositiy in star-forming galaxies, generally independent of galaxy morphology, star-formation rate, and star-formation intensity (e.g., Walterbos 1998). A notable exception is the observation of much lower WIM fractions in starburst galaxies (Oey *et al.* 2007). This may be related to the short starburst timescale relative to ISM recombination (Hanish *et al.* 2010), and underscores the need to better understand the relationship between star formation and WIM properties. Ultimately, clarifying the fate of ionizing photons will reveal whether and/or when they escape from their host galaxies altogether, a question of vital importance to cosmic reionization and evolution.

Based on energetic arguments, OB stars are understood to be the ionizing source for the WIM, with an important contribution from field OB stars (e.g., Hoopes & Walterbos 2000; Oey *et al.* 2004) and the rest from stars within optically thin HII regions, but the relative contributions are poorly known. In particular, the ionizing fluxes from OB stars are not known well enough to clarify this problem (e.g., Voges *et al.* 2007; Zastrow *et al.* 2012). It is therefore essential to obtain a comprehensive understanding of the radiation transfer of the HII regions in galaxies. The WIM emission-line spectra provide important constraints, implying long photon path lengths and significant contributions from leaking HII regions (e.g., Castellanos *et al.* 2002; Wood & Mathis 2004; see also A. Hill in these Proceedings). The WIM morphology also points to low opacities and the importance of dust scattering (Seon 2009; and in these Proceedings).

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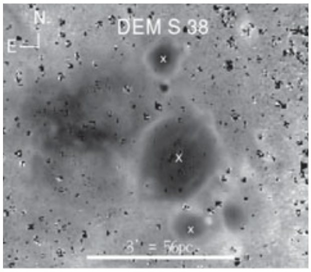

Figure 1. SMC HII regions in [SII]/[OIII], with high values white (Pellegrini *et al.* 2012).

2. Ionization parameter mapping

Here, we present our technique of ionization-parameter mapping, a new application of emission-line imaging to directly reveal the optical depth of ionized gas to the Lyman continuum (Pellegrini *et al.* 2012). Figure 1 shows the [SII]/[OIII] ratio map of some HII regions in the Small Magellanic Cloud (SMC) from the Magellanic Clouds Emission-Line Survey (MCELS; Smith *et al.* 2005). The large, round object, DEM S38, is dominated by the higher-ionization species, [OIII] (black); while the limb is dominated by the lower-ionization species, [SII] (white). The same effect is apparent in other objects marked with 'X' in the image. This ionization structure strongly suggests that these are classical Strömgren spheres, since the ionization must show a transition zone to lower-ionization species between the highly ionized center and the neutral environment. The round morphology is also consistent with that of the simple, Strömgren sphere.

In contrast, the object directly to the east of DEM S38 does not show the [SII]-dominated transition zones, and is instead dominated by [OIII] emission throughout. The object also has highly irregular morphology, which is consistent with radiation-hydrodynamic simulations by Arthur *et al.* (2011) that are characteristic of highly-ionized, optically thin objects subject to champagne flows and other gas instabilities. Thus, ionization-parameter mapping (IPM) offers a vivid, visual technique to directly estimate the nebular optical depth. We also note that IPM can be applied in the line of sight: since the low-ionization envelope must also exist in the line of sight, a minimum threshold emission from that species must be present across an optically thick object. Its absence therefore implies a low optical depth.

Thus, IPM provides a powerful way to evaluate the optical depth of HII regions. Pellegrini *et al.* (2012) discuss the reliability of this technique by carrying out photoionization modeling and comparison with objects having measured estimates of the optical depth. With only two radially varying ions, IPM technically tends to set upper limits to the optical depth, but in general, objects that look like Strömgren spheres with low-ionization envelopes indeed seem to be optically thick. And mapping three radially sensitive ions allows actual measurement of the optical depths.

3. Optical depth of Magellanic Clouds HII regions

We apply IPM to the Magellanic Clouds, using data from MCELS. IPM reveals the ionization structure, providing physical criteria for defining HII region boundaries. We use this to redefine all the HII regions in these two galaxies, compiling new nebular catalogs for both the LMC and SMC (Pellegrini *et al.* 2012).

The MCELS data provide only two radially varying species, [OIII] and [SII], and so optical depth estimates for individual objects are technically upper limits. However, the statistical properties for the nebular populations of the entire galaxies are revealing.

Classifying the objects simply as optically thick or thin based on IPM, we find that the frequency of optically thick objects correlates strongly with HI column density. While this is consistent with expectations, it is interesting to note that optically thin objects dominate in frequency at the very lowest HI columns. We also see a strong correlation in the frequency of optically thin objects with Hα luminosity L, although it is important to note that optically thick objects are found at almost all luminosities. Optically thin objects dominate in both galaxies above 10^{37} erg s^{-1}. Beckman *et al.* 2000 had suggested that high-luminosity HII regions tend to be density bounded, but we find that the characteristic luminosity is much lower. Indeed, 10^{37} erg s^{-1} corresponds to objects ionized by individual O stars, implying that most (but not all) of the bright HII regions that are readily apparent in star-forming galaxies are optically thin. It is especially interesting that trends for optical depth in both galaxies are so similar, given that their HI morphologies differ greatly; the LMC is a disk with strongly shredded HI, while the SMC has amorphous and less porous HI.

Overall, we find that about 40% of the HII regions in the LMC are optically thin, as are 30% of the objects in the SMC. In the aggregate, about 37% of the Lyman continuum radiation from their ionizing stars escapes to ionize the WIM in both galaxies. Given the total WIM luminosities and accounting for field star ionization, our results are consistent with escape fractions from the galaxies of 4% and 11%, respectively, for the LMC and SMC, although these values are quite uncertain (Pellegrini *et al.* 2012). Our results show that the galactic escape fractions are extremely sensitive to the location and HI environment of the few, most luminous objects.

In summary, ionization-parameter mapping is powerful technique for evaluating the optical depth of photoionized gas. Our results for the Magellanic Clouds yield fundamental, quantitative insights on the relation between optical depth, nebular luminosity, and HI properties. We are also applying the technique to starburst galaxies, which revealed the presence of an ionization cone in NGC 5253 (Zastrow *et al.* 2011).

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