Ionization by Massive Young Clusters as Revealed by Ionization-Parameter Mapping

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Abstract  Ionization-parameter mapping (IPM) is a powerful technique for tracing the optical depth of Lyman continuum radiation from massive stars. Using narrow-band line-ratio maps, we examine trends in radiative feedback from ordinary H\textsc{ii} regions of the Magellanic Clouds and nearby starburst galaxies. We find that the aggregate escape fraction for the Lyman continuum is sufficient to ionize the diffuse, warm ionized medium in the Magellanic Clouds, and that more luminous nebulae are more likely to be optically thin. We apply ionization-parameter mapping to entire starburst galaxies, revealing ionization cones in two nearby starbursts. Within the limits of our small sample, we examine the conditions for the propagation of ionizing radiation beyond the host galaxies.

1 Introduction

Massive young clusters are responsible for giant regions of ionized gas. These are photoionized by the clusters themselves, as well as shock-ionized by supernovae and supersonic stellar winds from the high-mass stars. Here, I will focus on the photoionized gas, which provides the emission-line diagnostics that are widely used to evaluate a variety of phenomena across the universe, for example, star-formation rate and ionizing stellar populations, as well as gas properties such as metallicity, density, pressure, and kinematics. Many papers presented in this conference exploit this technique, in particular, work by E. Telles and M. Rodriguez in this session. When considering global properties of galaxies, the H\textsc{ii} region luminosity function provides a quantitative parameterization of star formation. And finally, stellar radiation from optically thin H\textsc{ii} regions is responsible for ionizing the interstellar medium and thereby generating the diffuse, warm ionized medium (WIM).

It is therefore apparent that photoionization by massive stars in clusters not only provides essential diagnostics of physical conditions, but also is itself a fundamental process. What is the fate of ionizing photons? We clearly see H\textsc{ii} regions in the immediate vicinity of massive clusters, but a significant proportion of these regions must be optically thin, and thus ionize the WIM. Similarly, if the ISM is itself optically thin in some galaxies, then Lyman continuum radiation will escape into the circumgalactic medium and perhaps, the intergalactic medium. It is widely believed that this was the case in early cosmic times, and that massive stars are responsible for the reionization of the universe. Thus, photon path lengths likely range across

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many orders of magnitude. It is also important to keep in mind that when the photons are absorbed, whether near or far from their source, they not only cause ionization of matter, but also impart momentum, generating radiation pressure that may be significant to gas kinematics. This topic is explored by S. Silich in this session.

2 Ionization-Parameter Mapping

A central issue is therefore quantifying which H II regions are optically thin. Many studies have examined this problem using different strategies. While some authors model globally-integrated emission-lines (e.g., Iglesias-Páramo & Muñoz-Tuñon 2002; Giammanco et al. 2004), others model the WIM surface brightness generated by its opacity and scattering (e.g., Zurita et al. 2002; Seon 2009). Here, we demonstrate an elegant technique to evaluate the optical depth of H II regions based on ionization-parameter mapping (IPM), exploiting the fact that the nebular ionization structure varies between optically thin and optically thick objects.

![Image](image1.png)

**Fig. 1** Ratio map for [OIII]λ5007/[SII]λ6717 of SMC nebulae; black and white indicate high and low values, respectively. The objects marked by crosses exhibit classic, Strömgren sphere ionization structure. (N is up, E to the left; from Pellegrini et al. 2012.)

Figure 1 shows the [OIII]/[SII] emission-line ratio map for some H II regions in the Small Magellanic Cloud (SMC). In the case of an optically thick, Strömgren sphere, the ionization state will be high in the central regions near the ionizing source, and will decrease at large radii, as it transitions to the neutral environment at the nebular boundary. Thus, the nebular structure shows more highly ionized species, represented in Figure 1 by O++, in the center, surrounded by an envelope of lower-ionization species like S+. The round H II regions marked with crosses in Figure 1 demonstrate this classic, Strömgren sphere ionization structure. In contrast, the object with irregular morphology to the east in Figure 1 appears to be completely dominated by [OIII] and is missing the low-ionization envelope. This implies that the object is density-bounded and therefore optically thin. The irregular morphology is also consistent with radiation hydrodynamic simulations by Arthur et al. (2011).
H II Region and Starburst Optical Depths

showing that objects with the highest ionization parameters, which are the ones that become optically thin, develop instabilities leading to irregular morphology such as that seen in the eastern object of Figure[1].

However, exploration of the parameter space with simple photoionization models shows that this elegant picture is a bit more complicated. Using CLOUDY (Ferland et al. 1998) models, we demonstrated that for lower ionizing effective temperatures, low-ionization envelopes may be present even for quite optically thin conditions (Pellegrini et al. 2012; hereafter P12). Thus, for IPM based on only two ionic species, it is the absence of these low-ionization transition zones that implies low optical depth; whereas their presence merely implies a substantial likelihood of optically thick conditions. However, we note that optically thin objects that possess low-ionization envelopes occur for cooler stars, which tend to yield smaller and fainter H II regions. And as noted above, nebular morphology is also a diagnostic criterion. We tested IPM as an estimator of optical depth by applying the method to a dozen nebulae in the Large Magellanic Cloud (LMC) with known spectral classifications of the ionizing stars. We crudely estimated escape fractions $f_{esc}$ by assigning the objects as optically thick, thin, or blister objects based on their ionization structure. These categories were simply assigned values of $f_{esc} = 0, 0.6,$ and $0.3$, respectively. More accurate $f_{esc}$ for these objects were then measured by comparing the predicted versus observed H$\alpha$ luminosities. The extremely crude IPM estimates agree surprisingly well with the measured values, to 25% on average (P12).

So in general, we suggest that objects that look like Strömgren spheres usually are Strömgren spheres. Note that any low-ionization envelopes should also be detected in the line of sight; thus IPM diagnostics are not limited to projected radial analysis. Furthermore, we stress that with three or more radially varying ionic species, the resulting maps of the ionization structure will constrain the optical depth far more strongly, essentially allowing its direct measurement. We have obtained such data for M33, which will permit us to quantify this capability.

3 Optical Depth of H II Regions in the Magellanic Clouds

The data presented above for individual nebulae in the LMC and SMC were generated from the Magellanic Clouds Emission-Line Survey (MCELS; Smith et al. 2005), a narrow-band imaging survey in H$\alpha$, [O III], and [S II] of the entire star-forming extent of both Clouds. These data allow us to apply IPM to crudely estimate the optical depths of the entire H II region population in both galaxies. It is especially interesting to quantitatively compare these, given that the LMC and SMC have strongly contrasting neutral H I ISM: as seen in the H I surveys of these galaxies (Kim et al. 1998; Stanimirović et al. 1999), the LMC has a highly shredded, filamentary neutral ISM with high porosity, owing to extensive mechanical feedback from massive stars and its flat, disk structure; whereas the SMC has a more three-dimensional and diffuse H I distribution with much lower porosity due to its much lower specific star-formation rate (Oey 2007).
Using IPM, we crudely categorize all HII regions as optically thick, thin, or neither (see P12 for details). Figure 2 shows the frequency of optically thin objects as a function of H\(_{\text{I}}\) column density \(N(\text{H}_{\text{I}})\) measured within the nebular apertures for the LMC and SMC. As expected, the fraction of optically thin objects clearly decreases with \(\text{H}_{\text{I}}\) column. However, it is noteworthy that that the optically thin objects actually dominate at the lowest \(N(\text{H}_{\text{I}})\) in both galaxies. The value of \(N(\text{H}_{\text{I}})\) at which this occurs is higher in the SMC than in the LMC, owing to the SMC’s 3-D ISM structure. Furthermore, we also see that there are still optically thin objects even at the highest \(\text{H}_{\text{I}}\) columns. While the mean \(N(\text{H}_{\text{I}})\) for the optically thick objects is larger in both galaxies, the \(N(\text{H}_{\text{I}})\) distributions for the optically thick and thin objects are similar in shape (P12).

![Figure 2](left) Frequency of optically thin objects as a function of H\(_{\text{I}}\) column density observed in the H\(_{\text{II}}\) region aperture, for the LMC (top) and SMC (bottom). (From P12.)

![Figure 3](right) Frequency of optically thin objects as a function of H\(_{\alpha}\) luminosity, for the LMC (top) and SMC (bottom). (From P12.)

Figure 3 shows the frequency of optically thin objects as a function of H\(_{\alpha}\) luminosity \(L_{\text{H}\alpha}\) for the LMC and SMC. In both galaxies, there is a clear trend that the frequency increases with \(L_{\text{H}\alpha}\). Even so, we again note optically thick objects exist even at the highest values of \(L_{\text{H}\alpha}\). However, optically thin objects dominate in numbers above a value of about \(\log L_{\text{H}\alpha} \sim 37/\text{erg s}^{-1}\) in both galaxies. This low luminosity corresponds to objects ionized by single, mid-type O stars, implying that most of the bright H\(_{\text{II}}\) regions seen in star-forming galaxies tend to be optically thin. The \(L_{\text{H}\alpha}\) distributions for the optically thick vs thin objects differ far more strongly than the distributions of their \(N(\text{H}_{\text{I}})\) (P12).
The statistics for these populations indicate lower limits on the total nebular escape fraction of $f_{\text{esc}}$ = 0.42 and 0.40 in the LMC and SMC, respectively. From these, we can derive total “escape luminosities” of $\log L_{\text{esc}} / \text{erg s}^{-1} \sim 40.1$ and 39.2, respectively, representing the total potential H$\alpha$ luminosities allowed by these $f_{\text{esc}}$. Comparing $L_{\text{esc}}$ to observed WIM luminosities in the LMC and SMC of $\log L_{\text{H}\alpha} / \text{erg s}^{-1} = 40.0$ and 39.3, respectively, we find that not only are the $L_{\text{esc}}$ large enough to fully ionize the WIM, but also that the global escape fractions from these galaxies may be non-zero, when accounting for contributions from field OB stars having no associated nebulae (see P12 for details). If this is the case, IPM shows that $f_{\text{esc}}$ is likely dominated by a few objects in the galactic periphery, rather than the most luminous objects in the dominant, central star-forming regions.

### 4 Starburst Galaxies

The individual Magellanic Clouds nebulae show that the most luminous objects are more likely to be optically thin. If so, then entire starburst galaxies might also plausibly have large $f_{\text{esc}}$. However, many studies have evaluated this possibility with mixed results. Only two local starbursts have confirmed detections of the Lyman continuum (e.g., Leitet et al. 2013; Grimes et al. 2009), while a minority of Lyman-break galaxies show such detections (e.g., Iwata et al. 2009; Shapley et al. 2006). Absorption-line studies of local starbursts all imply optically thick conditions (e.g., Heckman et al. 2001; Leitherer et al. 1995).

We therefore apply the IPM technique globally to a sample of local starburst galaxies: Haro 10 (NGC 5253), NGC 3125, Henize 2-10, NGC 1705, and NGC 178 (Zastrow et al. 2013). We carry out mapping in [SIII] and [SII], using the Maryland-Magellan Tunable Filter (MMTF) at Magellan. The IPM technique is again proven, revealing a vivid ionization cone in Haro 10 (Zastrow et al. 2011; Figure 4) and NGC 3125. The remaining galaxies show no significant evidence of optically thin regions. The narrow morphology of the ionization cones suggests that galaxy orientation to the line of sight plays a major role in the detection of Lyman continuum and optically thin gas. Thus, significant values of galactic $f_{\text{esc}}$ may be more common than observations thus far imply.

While our sample is small, our results are also consistent with suggestions that a minimum star-formation intensity is needed to generate optically thin conditions (e.g., Fernandez & Shull 2011). It is also likely that a specific age range is necessary, corresponding to times after which mechanical feedback from the starburst has sufficiently shredded the ISM to facilitate the escape of ionizing radiation, but also before the ionizing stars have expired. This should be around 3 – 5 Myr, again consistent with the data from our small sample.

Finally, since IPM implies that optically thin objects generate enhanced ionization parameters, we suggest that objects with extreme ionization parameters may therefore have high $f_{\text{esc}}$. The presentation in a later session by A. Jaskot demonstrates that this scenario may indeed be likely (Jaskot & Oey 2013). Hence we see
that the technique of ionization-parameter mapping is a powerful tool on both local and galaxy-wide scales.

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