Predicted O-Star Lyman-Continuum Emission vs. H II-Region Luminosities in the LMC

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Abstract. We compare predicted Lyman-continuum emission rates from O stars in LMC OB associations to the observed Hα luminosities of the host H II regions. Our results yield a fraction of escaping hydrogen-ionizing radiation in the range 0–51%, which is consistent with the fraction of total galactic Hα luminosity contributed by the warm ionized medium in the LMC. We find examples of objects that are significantly density-bounded, while others appear to be radiation-bounded.

1. Introduction

What are the hydrogen-ionizing luminosities of massive stars? Among the many astrophysical phenomena that are directly affected by this question is an understanding of the warm, diffuse component of the interstellar medium (ISM). At present, O stars are generally considered to be the principal candidate source for ionizing the warm, ionized medium (WIM; e.g., Reynolds 1984, Abbott 1982), since they are virtually the only source capable of producing enough power to ionize a global component of the ISM. However, outstanding problems with the O-star ionization model remain to be resolved. Emission-line ratios of He I/Hα (Reynolds & Tufte 1995; Heiles et al. 1996) and [N II]/Hα (Rand 1997) have suggested that the ionizing spectrum of the WIM is softer than predicted from an O-star population. More recent work (e.g., Martin & Kennicutt 1997) suggests that this problem may not be as severe as had been thought. It is also unclear whether O-star ionizing photons are capable of travelling the large ($\gtrsim$ 100 pc) distances required to ionize the WIM. Preliminary modelling by Dove & Shull (1994) and Miller & Cox (1993) does suggest that the O-star hypothesis is compatible with photon mean-free-path lengths.

But a more direct way to test the O-star ionization model is to compare directly the expected Lyman-continuum (Ly-c) photon emission rates with observed H II-region luminosities. This will determine whether Ly-c radiation is indeed escaping from H II regions and is thereby available to ionize the WIM. To carry out such a comparison, it is necessary to have adequate constraints on O-star model-atmosphere predictions for the Ly-c fluxes. While these predictions are still largely uncertain, we are optimistic that they are nevertheless useful. The present contribution is a brief summary of a study presented in greater detail in Oey & Kennicutt (1997).

2. The Comparison

A direct comparison of predicted Ly-c emission rates and observed H II-region luminosities can be carried out for OB associations with a complete, classified census of the O stars present. A viable sample of such OB associations is available in the Large Magellanic Cloud (LMC), which provides the additional advantage of low extinction and a uniform distance to all the objects.

We have compiled spectral classifications for the O stars in this sample from the literature, and applied the conversion between spectral type and Ly-c emission given by Schaerer & de Koter (1997; SdK). The total Ly-c emission predicted from the individual stars are then summed for each association, and converted to a predicted Hα luminosity for the host H II region. A reddening correction derived from the stellar data is applied, to enable direct comparison with the nebular observations. The observed Hα luminosities are measured from recalibrated photographic data of Kennicutt & Hodge (1986).

Table 1. Observed and Predicted H II-Region Luminosities.

LH	DEM	Henize	n_*	$L_{\rm obs}/L_{\rm SdK}$	Reference
2	10B	N79 CE	7	0.81	Parker, unpublished
...	25	N185	1	8.57	Oey (1996)
6	31	N9	6	0.40	Oey (1996)
9, 10	34	N11	44*	0.66	Parker et al. (1992)
...	50	N186	3	2.00	Oey (1996)
38	106	N30 BC	8	0.61	Oey (1996)
47, 48	152, 156†	N44	35*	0.66	Oey (1996)
51, 54	192	N51 D	25*	0.83	Oey & Smedley (1997)
58	199	N144	22*	1.22	Garmany et al. (1994)
73	226	N148 I	4	0.93	Oey (1996)
83	243	N63 A	11	0.54	Oey (1996)
110	293	N214 C	1	1.09	Conti et al. (1986)
114	301	N70	7	0.20	Oey (1996)
117, 118	323, 326	N180	20	1.13	Massey et al. (1989)

*WR star excluded; DEM 199 contains 3 WR stars.
†Not including DEM 152A.

Table 1 shows the comparison between observed H II-region luminosities and those predicted from the O-star census. Column 1 provides the Lucke & Hodge (1970; LH) identification for the OB association, and columns 2 and 3 give the nebular identifications from the Davies, Elliott & Meaburn (1976; DEM) and Henize (1956) catalogues. In column 4, we give n_*, the total number of classified O stars present, where associations containing Wolf-Rayet (WR) stars are marked with an asterisk. In this study, we consider only the ionizing contributions of O stars, which should dominate the sample as a whole. Column 5 shows the actual comparison itself, the ratio of observed to predicted ($L_{\rm obs}/L_{\rm SdK}$) nebular Hα luminosity. Finally, column 6 provides the reference for the spectral classifications.

The objects in Table 1 show a median ratio of observed to predicted Hα luminosity $L_{\rm obs}/L_{\rm SdK} = 0.74$, excluding the two objects DEM 25 and DEM 50. These two objects may have significant contributions to the observed Hα luminosities from supernova remnants, and DEM 50 is also likely to have an incomplete census of O stars (see Oey & Kennicutt 1997). The median ratio of 0.74 is subject to substantial uncertainties. These are discussed in detail by Oey & Kennicutt (1997), but by far the dominant source of uncertainty is that introduced by the model-atmosphere predictions for the Ly-c emission rates. We therefore estimate that the overall median ratio of observed to predicted Hα luminosities is subject to roughly 50% uncertainty, which yields a median value of $L_{\rm obs}/L_{\rm SdK}$ in the range 0.49–1.1.

The median ratio of 0.74 for the observed to predicted Hα luminosity for the sample is in good agreement with results by Hunter & Massey (1990), who performed a similar comparison for faint Galactic H II regions. Their data show a median ratio of observed to predicted H II-region luminosity of 0.7, using the conversion between spectral type and Ly-c emission given by Panagia (1973). We note that Table 1 shows a range of $L_{\rm obs}/L_{\rm SdK}$ for individual nebulae, encompassing both density-bounded and ionization-bounded objects. Furthermore, the values in Table 1 suggest that the Ly-c predictions for O stars are unlikely to be off by more than 50%, since the range in ratios does include a reasonable range of both ionization-bounded and density-bounded objects.

While the comparison we show in Table 1 adopts the Schaerer & de Koter (1997) ionizing fluxes, we also experimented by using the tabulations of Panagia (1973) and Vacca, Garmany & Shull (1996). In addition, we found no significant correlation in $L_{\rm obs}/L_{\rm SdK}$ with nebular luminosity or morphology. We refer the reader to Oey & Kennicutt (1997) for details on these issues.

Thus we estimate an overall fraction of escaping Ly-c radiation in the range 0–51%. This is fully consistent with the fraction of the total Hα luminosity of the LMC contributed by the WIM, which Kennicutt et al. (1995) find to be $\sim$35$\pm$5%. Our results are also consistent with the WIM fraction in other nearby galaxies, which ranges 20–53% (see Ferguson et al. 1996). These results therefore continue to support O stars as the primary candidate source of ionization for the WIM. Alternative ionizing mechanisms are not ruled out, since our lower limit for the fraction of escaping ionizing radiation is formally 0%. However, in practice, our lower limit must be > 0 since Table 1 shows a number of individual objects that are convincingly density-bounded. It will be of great interest to obtain better constraints on the predicted ionizing fluxes of massive stars to gain further insight on the ionization of the WIM.

Acknowledgments. We wish to thank Paul Crowther, Daniel Schaerer, Keith Smith, and Bill Vacca for helpful discussions, and we are also grateful for comments received during the course of this workshop. We thank Joel Parker for access to spectral types for LH2. This research was supported in part by the US National Science Foundation through grant AST-9421145.

References

Abbott, D. C., 1982, ApJ, 263, 723

Conti, P. S., Garmany, C. D., Massey, P., 1986, AJ, 92, 48

Davies, R. D., Elliott, K. H., Meaburn, J., 1976, MemRAS, 81, 89 (DEM)

Dove, J. B., Shull, J. M., 1994, ApJ, 430, 222

Ferguson, A. M. N., Wyse, R. F. G., Gallagher, J. S., Hunter, D. A., 1996, AJ, 111, 2265

Garmany, C. D., Massey, P., Parker, J. W., 1994, AJ, 108, 1256

Heiles, C., Koo, B.-C., Levenson, N. A., Reach, W. T., 1996, ApJ, 462, 326

Henize, K. G., 1956, ApJS, 2, 315

Hunter, D. A., Massey, P., 1990, AJ, 99, 846

Kennicutt, R. C., Bresolin, F., Bomans, D. J., Bothun, G., Thompson, I. B., 1995, AJ, 109, 594

Kennicutt, R. C., Hodge, P. W., 1986, ApJ, 306, 130

Lucke, P. B., Hodge, P. W., 1970, AJ, 75, 171 (LH)

Martin, C. L., Kennicutt, R. C., 1997, ApJ, 483, 698

Massey, P, Garmany, C. D., Silkey, M., Degioia-Eastwood, K., 1989, AJ, 97, 107

Miller, W. W., Cox, D. P., 1993, ApJ, 417, 579

Oey, M. S., 1996, ApJ, 465, 231

Oey, M. S., Kennicutt, R. C., 1997, MNRAS, 291, 827

Oey, M. S., Smedley, S. A., 1997, in preparation

Panagia, N., 1973, AJ, 78, 929

Parker, J. W., Garmany, C. D., Massey, P., Walborn, N. R., 1992, AJ, 103, 1205

Rand, R. J., 1997, ApJ, 474, 129

Reynolds, R. J., 1984, ApJ, 282, 191

Reynolds, R. J., Tufte, S. L., 1995, ApJ, 439, L17

Schaerer, D., de Koter, A., 1997, A&A, 322, 598 (SdK)

Vacca, W. D., Garmany, C. D., Shull, J. M., 1996, ApJ, 460, 914

Discussion

Crowther: The WR stars in the inner region of 30 Dor contribute around 15% of the ionizing flux – slightly higher than you assume.

Oey: Okay. . . clearly, the relative numbers of WR:O stars depends on the ages.

Barlow: Wolf-Rayets are also a lot harder to miss than O stars, and may therefore tend to be over-represented.

Aufdenberg: Regarding 'leaking' photons, we may be able to measure this quantity directly in β CMa. We now have a very nice model fit to the EUV, shown in my paper [p. 127], and we also have a measured column, so we actually measure the EUV flux. Using a simple CLOUDY-type model you can then get a direct measure of the leakage. It turns out to be very small – about a half per cent.

Oey: The discrepancy between observed and modelled fluxes has been resolved?

Aufdenberg: Our line-blanketed models give better temperature structures.