H II REGIONS AND STAR FORMATION IN THE MAGELLANIC CLOUDS

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ABSTRACT. The H II regions in the Magellanic Clouds provide an opportunity to characterize the global star formation properties of a galaxy at close range. They also provide a unique laboratory for testing empirical tracers of the massive star formation rates and initial mass functions in more distant galaxies, and for studying the dynamical interactions between massive stars and the interstellar medium. This paper discusses several current studies in these areas.

1. Introduction

The H II regions in the Magellanic Clouds, besides being fascinating objects of study in their own right, are important benchmarks for studies of ionized gas and massive star formation in more distant galaxies. They are the only H II region systems which we can survey completely, from the smallest compact star forming regions to the 30 Doradus giant complex, and as such they provide fundamental information on the luminosity and mass functions of star forming regions. The H II regions also furnish a testing ground for the various diagnostic methods used to measure star formation rates, initial mass functions, and chemical abundances in galaxies. For most galaxies this information can only be obtained from modelling the integrated spectra of entire star forming regions, but in the Clouds the stars in the H II regions can be studied directly, and compared with what is predicted from the nebular spectra. Finally, the H II regions are optimal laboratories for studying the interactions and feedback between massive stars and the interstellar medium, since they provide an abundance of massive stars and supernovae, a dense surrounding interstellar medium, and an ionized, line-emitting gas which provides complete diagnositic information on the densities, temperatures, pressures, velocity fields, and energetics of the gas.

In this paper I will discuss what has been learned over the past decade about the H II region populations and massive star formation in the Magellanic Clouds, with special emphasis on the subjects mentioned above. This is not intended to be a thorough review, but rather a topical discussion of some of the main areas of current interest in this field. Related subjects, such as the abundances, spatial distribution, stellar populations, and kinematics of the H II regions, as well as the 30 Doradus region, are discussed in more detail elsewhere in this volume.

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2. Global Properties of the H II Region Populations

The original Hα emission surveys by Henize (1956) and Davies, Elliott, and Meaburn (1976) are still the most comprehensive catalogs of H II regions available. Several surveys since that time has been directed at obtaining quantitative data on the physical properties of the H II region populations. Braunsfurth and Feitzinger (1983) compiled data at a variety of wavelengths on the LMC H II regions and associations, and Kennicutt and Hodge (1986) measured Hα fluxes for complete samples of H II regions in both galaxies. A similar study, based on aperture synthesis radio continuum measurements, is being pursued by Turtle's group at Sydney. Dottori and Bica (1981), Caplan and Deharveng (1985, 1986), and Copetti and Dottori (1989) have measured photoelectric Hβ and/or Hα fluxes for large samples of H II regions, in order to study the behavior of the stellar populations and interstellar extinction.

The H II regions cover an enormous range in properties, with Hα luminosities ranging from $\sim 10^{36}$ $erg\ s^{-1}$, equivalent to the photoionized regions around one or a few late-type O stars, to nearly 10^{40} $erg\ s^{-1}$ for 30 Doradus. The lower limit is set by the sensitivity of the photographic emulsions in the original Henize and DEM surveys, but CCD surveys currently under way (*e.g.*, Wilcots and Hodge, this meeting) promise to reveal considerable numbers of fainter regions.

This large dynamic range make the Magellanic Clouds ideal objects for studying the form of the H II region luminosity and diameter functions. Above 10^{37} $erg\ s^{-1}$, roughly the luminosity of the Orion nebula, the luminosity function is well fitted by a power law, with slope $dN(L)/dL = 1.7 \pm 0.15$ (Kennicutt and Hodge 1986). This is characteristic of active star forming Magellanic irregular galaxies, but is much shallower than the slope measured for either the Milky Way (Smith and Kennicutt 1989) or other spiral galaxies (*e.g.*, Kennicutt, Edgar, and Hodge 1989). The difference is significant, and as discussed below may have important implications for the structure of the interstellar media in the galaxies. At lower luminosities the luminosity function turns over, but this occurs at about the same level where incompleteness in the H II region catalogs becomes important. The new CCD data will be needed to reliably determine the luminosity function at these levels.

The H II region diameters also show a thousandfold range (Henize 1956, Davies *et al.* 1976), and the form of the diameter distribution was investigated by van den Bergh (1981) and Kennicutt and Hodge (1986). The number distributions $dN(D)/dD$ for large H II regions ($D \geq 20$ pc) are represented extremely well by an exponential distribution, with an e-folding diameter of ~ 80 pc.

The largest H II regions in the Magellanic Clouds have luminosities corresponding to the combined ionizing powers of tens to hundreds of OB stars, and for such objects the Hα luminosities scale roughly in proportion to the number of ionizing stars. The shallow slope of the nebular luminosity function implies that the most of the massive star formation in the Clouds takes place in the large H II regions, each containing of order 10–1000 ionizing stars. The LMC is extreme in this regard, with roughly a fourth of its massive star formation occurring in 30 Doradus alone! This is quite different from the situation in a spiral like M31, where the nebular luminosity function is much steeper than an inverse square law, and most of the massive stars form in regions containing no more than a few OB stars. This distinction may have important effects on the dynamics and evolution of the interstellar medium, because the large H II regions provide conditions which are conducive for the development

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of large "supershell" structures from multiple stellar wind ejections and supernovae (*e.g.*, Mac Low and McCray 1988).

Photometry of the H II regions also allows us to derive estimates for the integrated luminosities and massive star formation rates in the Clouds. The resolved H II regions in the LMC produce a combined ionizing luminosity of $\sim 3 \times 10^{52}$ *photons* s^{-1} (Kennicutt and Hodge 1986); this includes a correction of 1 mag for extinction (Caplan and Deharveng 1985). The corresponding number for the SMC is 5×10^{51} *photons* s^{-1}, if a mean extinction of 0.5 mag at Hα is used. The star formation rates required to produce these luminosities are relatively modest, about 0.3 and 0.05 $M_{\odot}$/yr respectively for the LMC and SMC, if the calibration of Kennicutt (1983) is used. These results are only lower limits, however, because they do not include diffuse ionized gas, or ionizing radiation which escapes from the discrete H II regions. Both effects are probably significant, as evidenced by the spectacular filamentary emission which is revealed in deep Hα images of the Clouds. Furthermore there is direct evidence for the escape of ionizing radiation from at least one large H II region in the LMC (Massey *et al.* 1989). A conservative upper limit to the true star formation rates in the galaxies would be a factor of two higher than the numbers given above.

3. Structure and Physical Properties of the H II Regions

In addition to the surveys described above, considerable effort has been devoted to detailed studies of individual H II regions (*e.g.*, Heydari-Malayeri and Testor 1985, 1986; Heydari-Malayeri *et al.* 1988, Kennicutt 1984, Lortet and Testor 1984, Lee 1989, Copetti 1990, Greve *et al.* 1990). The small H II regions are probably similar to compact H II regions in the Galaxy, but the physical characteristics of the largest H II regions, such as 30 Doradus, N11, N44, or N159 in the LMC, or NGC 346 in the SMC, are quite distinct. These 'giant' H II regions are often characterized as either scaled-up versions of small Galactic regions such as the Orion nebula, or as clusters of compact regions, but neither of these physical descriptions is accurate. Among the many distinctions, the giant H II regions possess lower gas densities, lower extinction, and higher velocity dispersions than a typical compact star forming region in the Galaxy. The ionized gas often exhibits a composite thermal/nonthermal structure, as discussed in Section 5 below. Many of these structural differences may have their origin in the composite nature of the associated stellar population. The presence of evolved stars (*e.g.*, McGregor and Hyland 1981, Massey *et al.* 1989b) and supernova remnants (*e.g.*, Long *et al.* 1981, Chu and Kennicutt 1988b, c) in many of the large H II regions indicates that the stellar age spread is comparable to the lifetime of individual massive stars. This mixture of stellar masses and ages is quite different from a small H II region, which is usually dominated by the most massive single star (or few stars).

It is likely that analogs to most of the large H II regions in the Magellanic Clouds are also present in our own Galaxy (*e.g.*, Carina, W49, NGC 3603), but the 30 Doradus region is quite extraordinary, by far the most luminous and massive star forming region in the Local Group (Kennicutt 1984). Its ionizing luminosity of nearly 10^{52} *photons* s^{-1} is larger than the entire SMC, and corresponds to the combined luminosities of well over 1000 O stars. Although it probably contains as many massive stars as many early-type galaxies, the H II region is by no means unique, as nearby spirals such as M101, M83, M51, and NGC 2403 contain several regions of comparable size (Kennicutt *et al.* 1989).

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4. Stellar Content and IMF

The H II regions in the Magellanic Clouds provide an ideal environment for studying the formation and mass functions of massive stars, and extensive surveys have been conducted by groups at Meudon (*e.g.*, Heydari-Melayeri *et al.* 1987, Lortet and Testor 1984, 1988) and Boulder (Massey *et al.* 1989a, b). In addition extensive surveys of the 30 Doradus region are under way by several groups (see Walborn's review). Here I briefly mention a few results which are relevant to the broader study of star formation in galaxies.

Massey *et al.* (1989a, b) have used CCD photometry and spectroscopy of complete samples of blue stars in 3 H II regions to measure the form of the initial mass function (IMF) for massive stars. The mean IMF slope $d\psi(m)/dm \simeq -2.8$ in these regions, very close to that derived for the solar neighborhood by Scalo (1986). A question of great interest is whether the 30 Doradus giant H II region is characterized by a similar IMF. Preliminary work by Melnick *et al.* (1985) and Parker (private communication) suggests a considerably shallower IMF in that region.

As emphasized by Dottori and Bica (1981) and Copetti *et al.* (1985), the photometric and spectroscopic properties of the most luminous H II regions are dominated by the age and mass function of the embedded stellar populations, rather than by the one or two most massive stars, and in principle it should be possible to derive these properties from spectra of the H II regions. The regions in the Magellanic Clouds are especially important in this regard, because one can use measurements of the H-R diagrams of the stars to test the reliability of IMFs and ages predicted by the nebular models.

Another interesting result of these surveys has been the discovery of H II regions with nebular He II emission, in N159F and N44C in the LMC (Pakull and Angebault 1986, Stasinska *et al.* 1986), and N76 in the SMC (Garnett *et al.* 1990). If the gas is photoionized by hot stars, the observed level of helium ionization requires stars with temperatures of at least 70000 K (Stasinska *et al.* 1986, Garnett *et al.* 1990).

The source of this ionization is not entirely clear. Wolf-Rayet stars are prime candidates, as recent observations of some W-R nebulae in the Clouds reveal He II emission (Niemela 1990, Pakull 1990). At least one of the H II regions (N159F) may be ionized by radiation from an X-ray source (Pakull and Angebault 1986, Pakull and Motch 1989).

5. Kinematics, Dynamics, Nonthermal Structures

Smith and Weedman (1972) demonstrated that the large H II regions in the Magellanic Clouds are characterized by highly supersonic velocity dispersions, and Melnick (1977) showed that the velocity dispersion of H II regions is correlated with their sizes. In giant H II regions like 30 Doradus these 'turbulent' velocity dispersions are typically $15 - 40$ $km\ s^{-1}$, and these supersonic motions probably account for the highly filamentary structure of most of the giant H II regions.

The origin of these motions, and of the velocity–size correlation, is not completely understood. Terlevich and Melnick (1981) have argued that the dispersions reflect virial motion of H II regions and their associated star clusters, but high resolution observations of the H II regions in the Magellanic Clouds suggest that stellar winds and supernovae may be responsible for accelerating most of the gas.

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Meaburn (1984, 1988) and Chu and Kennicutt (1988a, c) have used high-dispersion echelle and Fabry-Perot spectroscopy to map the velocity fields in 30 Doradus and other large H II regions, and these data reveal numerous shell structures covering a range of size and velocity scales. The most spectacular objects are fast shells ($v_{exp} = 100 - 300\ km\ s^{-1}$), which kinematically resemble fast stellar wind blown bubbles or supernova remnants (Chu and Kennicutt 1988a). The core of 30 Doradus contains a large number of such shells, which occur both as isolated structures as well as large, composite supershells.

Other evidence for supernovae embedded in 30 Doradus and other H II regions include the detection of nonthermal radio sources (Mills *et al.* 1978, Ye 1989) and X-ray sources (Long *et al.* 1981, Chu and MacLow 1990, Wang and Helfand 1990). Several of these features are coincident with the optically detected fast shells (*cf.*, paper by Chu and Kennicutt in this volume).

The total kinetic energy in the shells is probably comparable to that in the low-velocity 'turbulent' component, and hence it is possible that massive stars provide the bulk of the kinetic energy in the surrounding H II region. The near coincidence between this energy and the gravitational binding energy of the complex is intriguing, as it suggests that 30 Doradus is nearly in a self-regulating star formation regime, similar to that postulated for galactic disks by Dopita (1985) and others.

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