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STARBURST ANATOMY: STELLAR AND NEBULAR PROPERTIES OF NEARBY GIANT H II REGIONS

William H. Waller[1]

RESUMEN

La descomposición de regiones H II gigantes cercanas en sus componentes nebulares y estelares, provee información fundamental para la interpretación de los brotes de formación estelares más distantes. Este trabajo resume avances recientes en el conocimiento de las poblaciones estelares y de la energía del gas en regiones H II gigantes.

ABSTRACT

Resolution of nearby giant H II regions into their stellar and nebular constituents provides fundamental insights for interpreting more distant and powerful starburst activity. Photometry and spectroscopy of ionizing clusters in the Galaxy, LMC, and SMC reveal no significant relation between metallicity and the slope of the power-law initial stellar mass function (IMF). *HST*/WFPC2 photometry of 3 giant H II regions in M33 also does not show any consistent trend involving metal abundance and IMF slope —contrary to predictions based on emission-line ratios. The upper stellar mass limit appears to be constrained more by cluster age than by anything else.

The ionizing luminosities from some of the resolved stellar populations are insufficient to account for the ionization rates inferred from measurements of the composite (integrated) Hα emission. Absorption of stellar EUV emission by nebular dust grains would only amplify these photoionizing shortfalls. Leakage of ionizing photons from the H II regions would further exacerbate the situation. What then is providing the additional ionization? Prospects for higher stellar EUV luminosities and/or alternative sources of nebular ionization (e.g., shocks) are evaluated with this question in mind.

Key words: **GALAXIES: STARBURST — ISM: DUST, EXTINCTION — H II REGIONS — STARS: EARLY TYPE — ULTRAVIOLET: STARS**

1. KEY QUESTIONS

A fundamental question regarding starburst activity in galaxies is "What are starbursts made of?" More specifically, (1) how are the ionizing stellar populations clustered, (2) how does the stellar initial mass function depend on starburst intensity, metallicity, and other environmental factors, and (3) what balance of radiative and mechanical processes powers the starburst nebulae? A full answer to these questions requires the ability to resolve the stellar and nebular constituents of the starbursts. Fortunately, this can be done for giant H II regions (GHRs) in the Galaxy and in other galaxies of the Local Group. The following discussion of stellar and nebular properties is intended to complement the related reviews by C. Leitherer, A. Moffat, and H. Zinnecker in these Proceedings.

2. STARBURST CONSTITUENTS VS. AVAILABLE RESOLUTION

The ability to resolve stellar and nebular structure in starbursts depends on the distance to the starbursting source, the source's degree of central concentration, and the angular resolving power that is available. The Orion nebula provides a handy benchmark for ascertaining the degree of resolution attainable with each source. Orion's central "Trapezium" cluster of hot stars spans approximately 15″ (0.04 pc), while its most prominent nebular feature —the ionization front to the SE— is roughly 10-times larger in extent (~0.4 pc). These stellar and nebular features can be resolved from the ground out to distances of ~ 10 kpc and 100 kpc respectively. Imaging with the *HST* extends the "fully resolved" stellar and nebular structures to distances of 100 kpc and 1 Mpc respectively. At the distance of M33 (0.84 Mpc), the dense clustering seen in Orion, NGC 3603, and 30 Doradus

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[1] Hughes STX Corporation, NASA Goddard Space Flight Center, Laboratory for Astronomy and Solar Physics, Code 681, Greenbelt, MD 20771, USA; E-mail (waller@stars.gsfc.nasa.gov).

1997RMxAC...6..123W

would remain partially resolved. And beyond 1 Mpc distance, the probability of mistaking compact clusters as point sources becomes problematic.

However, dense cluster formation is not universal to nearby starburst activity —despite the impressive numbers of luminous and compact clusters that have been found recently in starburst environments (Ho, this volume). Indeed, the degree of clustering is found to vary greatly among nearby starbursts— from compact "super star clusters" such as the R136 core in 30 Doradus, to the sprawling stellar populations evident in the giant H II regions of M33. For example, R136 contains about 17 000 stars ($M \geq 4\ M_\odot$) within a diameter of 10 pc, or roughly 2.3 times the number of stars that is scattered across the central 100 pc of NGC 595 —the second most massive GHR in M33 (Malumuth, Waller, & Parker 1996). *HST*/WFPC2 imaging of NGC 604, the most massive GHR in M33, reveals a similarly loose association of $\sim$ 35 000 OB stars sprawling over a 100 pc diameter field (Hunter et al. 1996). What these loosely clustered starbursts lack in central concentration is compensated through their larger sizes. Moreover, their less crowded populations enable stellar photometry and spectroscopy to be conducted in galaxies well beyond the "fully resolved" distance of 100 kpc.

The nebular structure of giant H II regions is exemplified by the exquisitely complex views of 30 Doradus and NGC 604 as obtained at Hα with ground based telescopes and the *HST*/WFPC2 (cf., Cheng et al. 1992; Hunter et al. 1995). In both GHRs, the embedded OB clusters have evacuated inner cavities which, in turn, enable them to illuminate myriad bright rims, loops, and bubbles in the surrounding gas. Coherent structures are evident on scales of $\sim$ 100 pc down to the resolution limit of $\leq$ 1 pc. The dynamical origins and current energetics of these nebular structures remain uncertain (see Section 4).

3. STELLAR POPULATIONS — A REMARKABLE CONSENSUS EMERGES

Composite indices of the stellar populations powering starburst activity include the broadband visible and UV colors, absorption-line strengths and ratios, hydrogen-line luminosities and equivalent widths, emission-line ratios, and far-infrared "excesses" relative to the radio Bremsstrahlung emission. Such composite diagnostics have led to claims of environmentally-sensitive IMFs. For example, studies of emission-line ratios in GHRs and H II galaxies indicate IMFs that are biased towards hotter, higher-mass stars in regions of lower metal abundance (Campbell 1987; Vilchez & Pagel 1988). Other studies involving the Hα equivalent width as a tracer of the high-mass IMF have found no metallicity dependence, but rather a sensitivity to dynamical factors such as shearing and tidal disruption in the disks of galaxies (Waller 1990; Waller & Hodge 1991). Even more provocative are multi-diagnostic studies which infer a high-mass bias in regions of especially intense starburst activity (Gehrz, Sramek, & Weedman 1983; Rieke et al. 1993).

Such claims of environmentally-sensitive IMFs depend on the assumption that one has correctly interpreted the various composite spectral indices. To evaluate the composite indices in terms of the actual stellar populations, it is first necessary to *resolve* and photometrically characterize the prominent members of the population. Spectroscopic follow-up of the hottest and brightest members is then necessary to constrain the temperatures, ionizing luminosities and masses of the stars most responsible for powering the composite spectral indices. In the past decade, considerable efforts have been made to characterize the stellar populations powering GHRs in the Galaxy and in other galaxies of the Local Group (see reviews by Leitherer, Moffat, and Zinnecker in these Proceedings). *What is remarkable is the degree of consensus that has been reached: In all nearby GHRs studied so far, the stellar IMF appears similar to that found in smaller clusters near the Solar neighborhood.*

Photometry and spectroscopy of ionizing clusters in the Galaxy, LMC, and SMC do not reveal any significant relation between metallicity and the slope (Γ) of the power-law IMF. Multi-band *HST*/WFPC2 photometry of 3 GHRs in M33 also does not show any consistent trend involving metal abundance and IMF slope (Hunter et al. 1995; Malumuth, Waller, & Parker 1996; Parker, Malumuth, & Waller 1996). Over a one-dex range of O/H abundances and a two-dex range of Hα luminosities, the IMF slopes of 11 GHRs average to $< \Gamma >= -1.3 \pm 0.2$ (Waller 1996). The upper-mass limit appears to be constrained more by cluster age than by anything else. And the proportion of lower-mass stars appears to be consistent with the derived IMF slopes down to detection limits of 2 $M_\odot$ in 30 Doradus and 0.2 $M_\odot$ in the Orion nebula (Zinnecker, this volume). The results from these resolved studies strongly differ with those based on the analysis of composite emission-line ratios (Campbell 1987; Vilchez & Pagel 1988; Vilchez et al. 1988) and other composite spectral diagnostics (Gehrz, Sramek, & Weedman 1983; Rieke et al. 1993).

4. NEBULAR ENERGETICS — BALANCING THE POWER

From the Orion nebula to the GHRs in M33, the ionizing luminosities of the resolved clusters barely account for the ionization rates that are inferred from measurements of the composite (integrated) Hα emission. In some GHRs significant *shortfalls of ionizing photons are measured relative to the gaseous ionization* (Malumuth, Waller & Parker 1996; Parker, Malumuth, & Waller 1996; Waller 1996). Absorption of stellar EUV emission by nebular dust grains could drastically amplify the photoionizing shortfalls (Aannestad 1989). Leakage of ionizing photons from the H II regions could further exacerbate the situation (Gonzalez-Delgado et al., Wall, this volume). What then is providing the additional ionization?

One possibility is that the ionizing luminosities of O-type stars have been underestimated. EUV fluxes of O-type stars have yet to be measured, and hence must be estimated by extrapolation of models based on UV and optical spectra. Currently, the only EUV measurement of an early-type star is of the B2 II star Epsilon Canis Majoris (Cassinelli et al. 1995). The resulting Lyman continuum luminosity of this star exceeds that predicted from optical and UV spectroscopy by a factor of 30!

Meanwhile, theoretical models of ionizing clusters are rapidly evolving, as new methods are developed for treating the EUV opacity in the hot and windy stellar atmospheres (Garcia-Vargas et al. 1995; Najarro et al. 1996). Some of these models predict strong declines in the EUV luminosities with increasing metallicity, possibly explaining the downturns in Hα equivalent widths and [O III]/[O II] line ratios that are observed at higher metallicity (Waller 1990; Campbell 1987; Vilchez & Pagel 1988; Vilchez et al. 1988; Shields 1990). Other models which include powerful stellar winds are able to reduce the EUV opacities and thereby increase the ionizing luminosities well-above those predicted by the less windy models (Najarro et al. 1996).

Another possible explanation for the apparent shortfall of ionizing luminosity from the resolved clusters is that shock waves are contributing significantly to the nebular ionization. Sufficiently strong shocks can arise in the bubbles blown by high-mass stars, in the supersonic turbulence generated by out-gassing virialized low-mass stars, and in the filamentary shells that are driven by supernova explosions (cf., Losinskaya 1992; Tenorio-Tagle et al. 1996). All of these energetics are present in giant HII regions, whose contents can include $10^5 - 10^6$ of low-mass stars with supersonic velocity dispersions, hundreds of O stars, tens of WR stars exhibiting superwinds, and the potential for tens of supernovae every Myr (Malumuth, Waller, & Parker 1996).

Constraining the various sources, sinks, and pathways of power in nearby GHRs remains an important challenge. Towards this end, several investigations of the resolved stellar and nebular properties in GHRs are in progress. By addressing *both* the radiative and mechanical energetics, these studies will provide fundamental insights for interpreting the unresolved activity in more distant and powerful starbursts.

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