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Discussion: Star Formation Within Galaxies

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Abstract.
This Discussion session focused on star formation within galactic scales. We attempt to identify the dominant physical processes and parameters that characterize star formation, and to identify key questions that illuminate these phenomena. The Discussion was delineated by the following cycle of three questions: (A) Is the top of the H II LF physically distinct? (B) How does massive star feedback affect the ISM and star formation? (C) How do ISM properties affect the H II LF? Finally, is one of these three questions the fundamental one of the cycle?

Corresponding answers emerged from the Discussion: (A) The H II LF to date is a continuous power law; (B) There are both positive and negative feedback effects, which are poorly understood; (C) The H II LF appears remarkably independent of ISM properties. Therefore, we suggest that the resultant fundamental question is: *"Is the* H II *LF and parent stellar cluster membership function universal?"* This is analogous to the related question of a universal stellar IMF. Understanding the relationship, if any, between the IMF, cluster membership function, and ISM properties may finally lead to a quantitative theory of star formation.

1. Introduction

As is suggested by the title of this conference, star formation is one of the fundamental drivers of evolution in the Universe. It can be considered on scales ranging from individual stars, to starbursts, to the cosmic history of star formation itself. Roberto Terlevich has spent much of his career considering this entire range of star formation events and interpreting the underlying physical processes that drive the evolution of galaxies and the Universe.

In this discussion session, we consider star formation within galactic scales. We attempt to make sense of the various phenomena related to star formation, and we try to identify the dominant processes that affect it. In organizing the topics for the discussion, each of us (CMT & MSO) independently compiled a list of our favorite relevant questions. We found that these issues all appear to fall within the confines of the following three major questions:

- **A. Is the top of the H II LF physically distinct? What determines spatial concentration of star formation and starbursts?**
- **B. How does massive star feedback affect the ISM and star formation?**
- **C. How do ISM properties such as metallicity, clumpiness, turbulence, and phase balance affect the H II region luminosity function (H II LF) and star formation?**

These three questions form a cycle: The H II LF and especially, the most luminous star-forming regions, determine the nature of massive star feedback; feedback drives properties of the interstellar medium (ISM); and ISM properties presumably must affect the H II LF. Is one of these three questions, A, B, or C, the fundamental determinant of the other two, and thereby of galactic star formation in general? How did this seemingly chicken-and-egg cycle originate? Are there actually external relevant issues that break the cycle? The discussion session raised a number of observational and theoretical issues that address these questions. In §5 below, we nominate our choice for The Fundamental Question.

2. A: The H II LF and starbursts

The H II region luminosity function is remarkably robust. Observations over a wide range of galaxy types consistently show that the differential LF is described by a power law of slope -2 ± 0.3. This is found for disk galaxies (e.g., Kennicutt, Edgar, & Hodge 1989; Banfi et al. 1993; Rozas et al. 1996), including those with active nuclei (González-Delgado & Pérez 1997). Oey & Clarke (1998) show that variations in the H II LF, including observed slope breaks and the apparently steeper slopes of Sa galaxies (Caldwell et al. 1991) are almost all consistently explained by a universal power law,

$$N(N_*)\ dN_* \propto N_*^{-2}\ dN_* \quad , \tag{1}$$

for the number of clusters having N_* ionizing stars in the range N_* to $N_* + dN_*$. The only apparent exception appears to be somewhat flatter slopes of -1 to -1.5 found in a study of dwarf irregular galaxies (Youngblood & Hunter 1999), although the H II region statistics in these small galaxies are more difficult. The universal power-law N_*^{-2} is also seen for stellar clusters themselves (Elmegreen & Efremov 1997).

But what about the upper limit to the H II LF? We see that it can vary between different galaxies: Oey & Clarke (1998) and Kennicutt et al. (1989) find that early-type spirals show a cut-off in the maximum luminosities of the star-forming regions around Hα luminosities of $\log L_{\mathrm{H}\alpha} \sim 38$ whereas late-type galaxies do not appear to show any maximum $L_{\mathrm{H}\alpha}$, often having H II regions with $\log L_{\mathrm{H}\alpha} \sim 41-42$. In the most actively star-forming galaxies, are the most vigorous star-forming regions a physically distinct class of objects from the rest of the nebular population?

The most active star-forming regions in many disk galaxies are the circumnuclear regions, which are often associated with bar activity. Although the central galactic areas should host conditions that are significantly different from the remainder of the disk, Alonso-Herrero & Knapen (2001) found that the H II LFs for circumnuclear H II regions in 52 galaxies nevertheless show remarkably normal slopes. Thus, these luminous star-forming regions simply represent an extension to the H II LF of the disks. Alonso-Herrero reports that preliminary analysis of photometric broadband observations of luminous infrared galaxies thus far confirms that the parent stellar clusters likewise appear to be scaled-up versions of those found in less luminous H II regions. Direct observations of super star clusters in starburst galaxies also confirms the N_*^{-2} power law in this regime (Meurer et al. 1995).

Nevertheless, it is apparent that the circumnuclear H II regions are systematically far brighter than the disk objects. This implies that nuclear conditions favor the formation of the most luminous regions. Another environment that favors highly luminous star formation is found in gas-rich dwarf galaxies, which also host some of the largest star-forming regions. The high-density, high-pressure, high-shear environment near galactic nuclei would appear to greatly contrast with the environment typically associated with the ISM in dwarf galaxies. Could these two types of environment have common dominant variables that induce energetic star formation? Are there differences between the giant H II regions formed in these respective conditions? From the discussion, it emerged that the formation of these luminous objects is probably determined by more complex factors than a single determining parameter like gas density, or else it would have been apparent by now. More likely, a combination of factors may dominate, for example gas density and freefall timescale, which together could produce similar conditions and high star formation in both of the environments identified above.

Another factor that must clearly limit the maximum H II region luminosities is the physical size of the host galaxy. The largest scales of star formation approach the physical scales of the host galaxy, for example in starbursts and H II galaxies. Does this factor affect the properties of the most luminous H II regions? There appears to be no evidence to date that it does. This suggests that star formation can be a highly localized effect, that need not be strongly influenced by the extended ISM properties of the host galaxies.

3. B: Massive star feedback and the ISM

The properties of massive star feedback vary, depending on the characteristics of the parent star formation, and host galaxy ISM and environment. For ordinary star-forming galaxies, continuous low-level or moderate star formation following the H II LF may produce only pockets of hot (10^6 K) gas in supernova-driven superbubbles, and some spatially scattered nebulae within a diffuse warm (10^4 K) ionized medium (WIM). However, feedback from high star-formation rates can be strongly dependent on, e.g., the spatial distribution of the star formation, and the properties of the surrounding galactic halo or intergalactic medium (IGM). Clarke & Oey (2002; see Oey & Clarke, this volume) show that, for the same high star formation rate, events that are spatially distributed and following the H II LF will shred the neutral ISM into worms and filaments, thereby strongly enhancing the escape of ionizing photons and metals from galaxies. Centrally concentrated star formation, on the other hand, would allow the escape of photons and material only through the opening angle of the central superwind cone. The ISM in the latter case would remain largely intact outside the central region. Similarly, the fate of hot gas and newly synthesized metals depends not only on the luminosity of the star-forming regions relative to the galactic gravitational potential, but also on the halo and external medium. Silich & Tenorio-Tagle (2001) and Kunth et al. (2002) emphasize the difficulty in ejecting material in the presence of external IGM pressure (see also the Tenorio-Tagle & Vílchez Discussion session, this volume).

Whether or not photons and material escape from galaxies will profoundly affect the ISM of the parent galaxies themselves. If ionizing photons cannot escape, then they are absorbed in the ISM and contribute to a more strongly ionized diffuse WIM. Presumably this heating will act to inhibit star formation. If hot gas and metals cannot escape the galaxy, they too, are returned to the host ISM. The metals will enhance cooling and thereby presumably enhance star formation; the hot gas will enhance mixing of these metals throughout the galaxy, depending on its spatial distribution. In short, the phase balance of the ISM is largely determined by the character of the massive star feedback. Interstellar turbulence is another consequence of mechanical feedback that must strongly affect star formation. While turbulent motion itself inhibits gravitational collapse, turbulence also restructures the multiphase ISM, perhaps promoting the formation of cold clouds.

On global scales, the above arguments suggest both negative and positive effects of feedback on star formation. Which dominates? On more localized scales, there are well-documented examples in the Large Magellanic Cloud of sequential star formation, apparently triggered by expanding superbubble shells (e.g., Dopita et al. 1985; Parker et al. 1992; Oey & Massey 1995). Circumnuclear rings or ring galaxies show evidence of propagating star formation, for example, NGC 1068 (Myers & Scoville 1987), probably triggered by nuclear activity; and the Cartwheel Galaxy (Marcum et al. 1992), triggered by a galaxy merger. Díaz reports tentative evidence of both radial and azimuthal age gradients in circumnuclear H II regions. Yet, as often argued for star formation at the molecular cloud scale, massive star feedback is also thought to destroy clouds and suppress star formation. On global scales, feedback in dwarf galaxies may result in the blowaway of a significant fraction of the ISM, also inhibiting star formation. Understanding how feedback affects star formation on both large and small scales remains a key open question.

4. C: The ISM and the H II LF

How do ISM properties yield the N_*^{-2} power law and resulting H II LF? This is a question that parallels the long-standing problem regarding the origin of the stellar initial mass function (IMF). Presumably fundamental properties of the ISM determine the H II LF. However, the above discussion in §2 emphasized that N_*^{-2} power law is remarkably constant, even for extremely different populations of objects, including low-luminosity H II regions in early-type galaxies, and high-luminosity circumnuclear regions. This suggests that the conditions causing the parent cluster membership function are remarkably insensitive to

ISM conditions. Since fundamental ISM parameters are density, pressure, and temperature, Lynden-Bell offers the analogy of star formation as a phase transition. A more complex phase transition than that of simple matter, to be sure, but perhaps a secure place to return to first principles?

Melnick noted the similarity between the N_*^{-2} power law and the IMF power-law index of -2.35 (Salpeter 1955). Fractal structure has long been a popular model for the ISM, and he suggested that the -2 power law simply results from a fractal default for complexity in nature. A difficult aspect of this model is that it appears to be unrelated to any specific physics, and therefore can only be tied to physical properties by circumstantial evidence. One of the most popular links is between fractals and interstellar turbulence (e.g., Norman & Ferrara 1996; see Oey 2002), since the latter yields a similar power law for the spatial power spectrum. However, it is now emerging that much of the large-scale neutral hydrogen in the ISM is strongly filamentary (Braun 1997; Elmegreen et al. 2001) which is difficult to reconcile with a simple fractal structure (Elmegreen et al. 2001).

The discussion inevitably moved to the analogous problem regarding the origin and constancy of the IMF. While some observations, for example, inferences of star formation rates in distant galaxies, are most consistent with a top-heavy IMF, there is little direct evidence locally for variations. Resolved observations of stellar clusters and unresolved observations of galaxies, for example, the existence of the Fundamental Plane, almost all point to minimal variations in the IMF.

5. The Fundamental Question

In the above cycle (A) $\rightarrow$ (B) $\rightarrow$ (C) $\rightarrow$ (A), is one of these three issues more truly fundamental than the other two? For example, it is hard to conclude that Question (B), the effect of feedback, is fundamental since feedback cannot occur without stars. On the other hand, without feedback-induced properties like turbulence and metallicity, the ISM would be drastically different than is found in present star-forming conditions. Thus primordial conditions may be excluded from this cycle in any case. Furthermore, preliminary evidence emerging from the above discussion shows that the N_*^{-2} cluster membership function and signature H II LF are remarkably constant; thus the short, radical(!) answer to Question (C) might be that ISM properties *don't* affect and the H II LF and the cluster membership function.

For our present state of knowledge, Question (A) therefore emerges from this Discussion as outstanding from the cycle. We might reword it: "Is the slope of the cluster membership function universal?" The extreme conditions of the most luminous star-forming regions naively would seem to offer a regime where variations might be found, analogous to the suggestions that this energetic regime promotes an altered, top-heavy stellar IMF. To date, however, the evidence does not show any such variations in the N_*^{-2} law. What is the origin of this law, and does it have any relation to ISM properties? We hope future discussions and arguments will focus on, and resolve, this issue.

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