Star Formation in Subcritical Environments

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Abstract. At large galactocentric distance in spirals, stars can form in a subcritical environment where the local surface gas density is lower than the critical density required to trigger large-scale massive star formation. Preliminary results related to this subcritical regime have been obtained for the nearly face-on ScI galaxy NGC 628 in which we have identified and measured the fluxes of 137 small HII regions at R>R25. A majority of these HII regions are located in two faint outer spiral arms easily seen in HI maps. The faintest HII regions that could be measured have fluxes only of a few times 10^{-16} erg cm^{-2} s^{-1}, corresponding to luminosities of \sim 10^{36} erg s^{-1}, or a fraction of the Orion Nebula luminosity. We discuss the impact of the subcritical regime on the shape of the HII region luminosity functions in galaxies.

1. Introduction

Starbursts are well-known loci of short episodes of massive star formation. However, massive stars also form in subcritical environments at a slower and more continuous rate. This regime seems to dominate in the outer disks of spirals, in low surface brightness galaxies and in quiescent dwarf galaxies.

Subcritical environments are characterized by low metallicities and surface gas densities inferior to the critical density required to form massive stars (Toomre 1964). Star formation in these environments is thought to occur in a stochastic manner without amplifying mechanisms such as spiral arms, bars, shock waves or interactions. The HII regions found in such regime are generally smaller, less luminous (by 100 to 1000 times) and isolated compared to their inner disk counterparts \(\text{R} \leq \text{R}_{25}\). We have initiated a full investigation of the subcritical regime for several spirals of different Hubble types. In this note, we discuss the first results on the HII region luminosity functions of the outer \(\text{R} > \text{R}_{25}\) and the inner disk \(\text{R} \leq \text{R}_{25}\) of NGC 628.

1 \text{R}_{25} \text{ represents the radius of the 25 B mag isophote.}
2. Observations

NGC 628 is a nearby (D = 10.4 Mpc), nearly face-on Sc(s)I galaxy. A total integration of 33000 seconds at Hα obtained at the 1.6 m telescope of the Observatoire Astronomique du Mont Mégantic revealed 137 HII regions at R>R25 (R25 = 15.7 kpc) (figure 1). Lelièvre & Roy (2000) have fully characterized these HII regions (location, flux, luminosity, star formation rate (SFR)). The faintest HII regions we measured at S/N ≥ 5 have fluxes of only a few times 10^{-16} erg cm^{-2} s^{-1}, which corresponds to luminosities of ~10^{36} erg s^{-1} or a fraction of the Orion Nebula luminosity (L~10^{37} erg s^{-1}). The Toomre instability criterion as well as the Schmidt law indicate that the ISM may become subcritical to star formation at around 20 kpc in NGC 628 (Lelièvre & Roy 2000), a radius corresponding to where the spiral pattern weakens. It might also indicate that those instability criteria are more sensitive to macroscopic influences like spiral density waves. In a recent investigation of several Irr galaxies (thus lacking spiral pattern), Hunter et al. (1999) showed that currently used instability criteria fail to predict the location where the ISM should become subcritical in Irr. In the following section, we explore how the transition from a regime of vigorous star formation (strongly amplified by spiral arms at R≤R25) to a more quiescent one (R>R25) could influence the shape of the HII region luminosity functions in spirals.

![Image of NGC 628 with stellar continuum subtracted. The black circle corresponds to R=5.2 arcmin (15.7 kpc).](image)

Figure 1. Hα image of NGC 628 with stellar continuum subtracted. The black circle corresponds to R=5.2 arcmin (15.7 kpc).

2.1. Luminosity Functions: inner disk vs extreme periphery

The HII region luminosity function (LF) in galaxies allows to study the influence of the global properties of galaxies (internal dynamics, chemical abundance,
spiral arms) on the massive star formation processes (Kennicutt et al. 1989). The number of HII regions per luminosity unit is generally described by a power law \( N(L) = AL^a dL \). The exponent \( a \approx -2 \) but it varies with the Hubble type as well as between the arm and interarm zones in a given galaxy (Kennicutt et al. 1989, Banfi et al. 1993, Rand 1992).

We used the percentage-of-peak photometry method of McCall et al. (1996) to derive the LF in NGC 628. The LF is steeper in the outer disk \((a = -2.4 \pm 0.2)\) than in the inner disk \((a = -1.6 \pm 0.1)\) (Figure 2). In both cases, the turnover luminosity is at \( \log L \sim 37.0 \). The LF is shallow at fainter luminosities and is almost flat from \( \log L = 36.2 \) to \( \log L = 37.0 \). Our sample suffers from incompleteness below \( \log L = 36.4 \), but we are confident about its near-completeness for \( L > 10^{36.4} \) erg s\(^{-1}\). Thus the break at \( \log L \sim 37.0 \) is probably real. The HII regions at \( R > R_{25} \) are well separated and do not suffer important crowding effects. The flatness of the slope at \( \log L < 37.0 \) could represent the regime of HII regions ionized by single stars (McKee & Williams 1997).

![Figure 2. Comparison of the luminosity functions of HII regions at R>R_{25} (open circles) and at R<R_{25} (filled circles).](image)

Variations in the slope \( a \) of HII LFs have been interpreted in terms of aging, cluster mass distributions, and initial mass functions (von Hippel & Bothun 1990; McKee & Williams 1997; Feinstein 1997; Oey & Clarke 1998). The latter authors have suggested that the steepening of the LF slope can be explained by a simple trend in upper cutoff of the distribution of \( N_* \), the number of stars per cluster. It need not involve a change in the slope \( \beta \) of the distribution of \( N_* \). This explanation for the different apparent behavior in the extreme outer disk of NGC 628 could be validated by HST imaging of the stars inside HII regions of nearby galaxies.

### 2.2. Comparison with M33

Similar results about luminosity functions have been obtained for other spirals. For instance, Wyder et al. (1997), in computing the luminosity function of M33, show that a turnover occurs around \( \log L \sim 36.5 \). Moreover, their best-fit slope...
of the bright end of the luminosity function is \( a = -2.40 \pm 0.15 \). This is exactly the same value we obtained for the outer disk of NGC 628. Spiral arms in M33 are not very well defined and thus, the environment where massive stars form in that galaxy could be similar to that at \( R > R_{25} \) in NGC 628. However, we need to observe more spiral galaxies belonging to different Hubble types before concluding about a possible dependence between the slope of the bright end of the luminosity function and the strength of the spiral pattern. Increasing the number of galaxies in our sample will also give better statistics on the LF of the interarm region (where the spiral pattern disappears).

Finally, LFs could be affected by a possible degeneracy in different kinds of subcritical environments. For instance, whereas Irr galaxies and the outer disks of spirals often exhibit a subcritical regime, the slopes \( a \) of their LFs are very different, ranging from \( \sim -2.5 \) for intermediate-type giant spirals to \( \sim -1.5 \) for irregular dwarfs. This difference in the general luminosity distribution could be explained by the different environments characterizing these two types of galaxies.

3. Conclusion

Deep H\( \alpha \) imaging of the nearly face-on ScI galaxy NGC 628 has revealed 137 faint, small, and isolated HII regions at \( R > R_{25} \). The majority of them fall along two main groupings looking like weak spiral arms. The LF displays a soft turnover at \( \log L \sim 37 \) and is steeper in the outer disk \( (a = -2.4 \pm 0.2) \) than in the inner disk \( (a = -1.6 \pm 0.1) \). This variation in slope could be used to investigate the subcritical regime of star formation.

References

von Hippel, T., & Bothun, G. 1990, AJ, 100, 403