Massive star formation in Luminous Infrared Galaxies

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Abstract. We present HST/NICMOS observations of a sample of LIRGs. We show that active star formation appears to be occurring not only in the bright nuclei of these galaxies, but also in luminous super-star clusters and giant H\textsc{ii} regions with ages of up to 20–40 Myr. This population of bright clusters and H\textsc{ii} regions is unprecedented in normal galaxies and emphasizes the effects of the extreme star formation in LIRGs.

1. Introduction

Luminous and ultraluminous infrared galaxies (LIRGs and ULIRGs, with $L_{\text{IR}} = 10^{11} - 10^{12} L_\odot$ and $L_{\text{IR}} > 10^{12} L_\odot$, respectively) have long been recognized as one of the best laboratories to study the process of violent star formation in the Local Universe. The dust-rich environments of LIRGs and ULIRGs are thought to be similar to the conditions in which star formation occurred at high redshift. The Hubble Space Telescope (HST) is proving to be an invaluable tool for unveiling the star formation processes in galaxies over spatial scales previously unattainable – scales of a few tens of parsecs. Most remarkable is the discovery of the so-called super star clusters (SSC) in interacting/merging galaxies (e.g., the Antennae). Although there is no precise definition, SSCs are massive star clusters with luminosities a few orders of magnitude brighter than globular clusters (see a recent review by Whitmore 2000). It is now clear that this population of SSCs is not only inherent to interacting galaxies, but also to LIRGs (see e.g., Alonso-Herrero et al. 2000; 2001; 2002), ULIRGs (Scoville et al. 2000), groups of galaxies (Gallagher et al. 2001) and even isolated galaxies (e.g., Maoz et al. 2001).

One of the main difficulties in quantifying the age of SSCs in LIRGs and interacting galaxies is breaking the age-extinction degeneracy. This usually translates into only rough age estimates for SSCs – 5 and 900 Myr, from photometric data (Whitmore 2000). H\textsc{ii} regions, on the other hand, will highlight the youngest regions of star formation, with ages of $< 5 - 10$ Myr, as these are the lifetimes of the O and B stars required to ionize the gas. In this paper we analyze the physical properties of H\textsc{ii} regions and star clusters in a sample of LIRGs, as well as their relation and evolution to provide further insight into the nature of the off-nuclear star formation in LIRGs.
2. Sample and Observations

We have selected a sample of eight LIRGs with both HST/NICMOS narrow-band Pa\(\alpha\) (\(\lambda_{\text{rest}} = 1.87\,\text{µm}\)) images and broad-band \(H\) (1.6\,µm) continuum images (Table 1) to identify \(\text{H}\,\text{II}\) regions and star clusters, respectively.

| Galaxy   | log \(L_{\text{IR}}\) (\(L_\odot\)) | Dist (Mpc) | FOV of Pa\(\alpha\) (kpc\(\times\)kpc) | log \(L(H\alpha)_{\text{tot}}\) (erg s\(^{-1}\)) | \(L_{\text{nuc}}/L_{\text{tot}}\) |
|----------|-------------------------------------|------------|----------------------------------------|---------------------------------|------------------|
| NGC 6808 | 10.94                               | 46         | \(11 \times 11\)                       | 41.38                           | \(\simeq 0\)     |
| NGC 5653 | 11.01                               | 47         | \(11 \times 11\)                       | 41.72                           | \(\simeq 0\)     |
| Zw 049.057 | 11.22                                | 52         | \(4.9 \times 4.9\)                     | 41.21                           | –                |
| NGC 3256 | 11.48                               | 37         | \(3.5 \times 3.5\)                     | 42.11                           | 0.41             |
| NGC 1614 | 11.62                               | 64         | \(6.4 \times 6.4\)                     | 42.60                           | 0.65             |
| VV 114   | 11.62                               | 80         | \(9.3 \times 9.3\)                     | 42.55*                          | 0.37             |
| IC 694   | 11.91                               | 42         | \(3.8 \times 3.8\)                     | 41.95                           | 0.58             |
| NGC 3690 | 11.82                               | 97         | \(9.2 \times 9.2\)                     | 43.19*                          | 1*               |

Notes. — Column (1): Galaxy. The two components of Arp 299 are usually referred to as IC 694 and NGC 3690. Column (2): IR (8 – 1000\,µm) luminosity. Column (3): Distance. Columns (4) and (5): Area imaged in Pa\(\alpha\) and \(H\alpha\) luminosity over that area. Column (6): Ratio of the nuclear to total \(H\alpha\) luminosity. * Uncertain because of the large correction needed to account for the total Pa\(\alpha\) flux (see AAH02 for details).

3. Super Star Clusters

Much of the recent star formation in our sample of LIRGs appears to be occurring not only in the bright nuclei, but also in luminous clusters and \(\text{H}\,\text{II}\) regions (e.g., Table 1, last column), similar to those found in other interacting and highly luminous IR galaxies (e.g., Scoville et al. 2000; AAH02). The absolute \(H\)-band magnitudes for clusters in LIRGs (not corrected for extinction) range up to approximately \(M_H = -17\) mag to \(M_H = -18\) mag (see histogram for the clusters of NGC 3256 in Fig. 1, left panel). The lower detection limit depends on the emission from the underlying galaxy and the degree of crowding. For instance the distribution of \(H\)-band luminosities of clusters detected in NGC 3256 appears to be complete down to \(M_H \simeq -14\) mag (Fig. 1).

The luminosities of the brightest IR clusters in LIRGs may exceed the limits found in more normal conditions. For example, the intermediate-age clusters in M100 (Ryder & Knapen 1999) have \(M_H = -12\) mag to \(M_H = -15\) mag assuming \((H - K \simeq 0.2)\). Since the IR luminosities change only slowly with time after approximately 20 million years (see Fig. 2), we can compare directly to see that the luminosities of clusters in normal galaxies may be about 1.5 – 2 mag lower than for LIRGs. Even when compared to starburst galaxies, LIRGs appear to have an excess of luminous IR clusters, as illustrated in Fig. 1 (left panels). This figure compares the distribution of luminosities of clusters in the central region...
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of the starburst galaxy NGC 1530 (at a distance similar to NGC 3256 and thus same spatial resolution) with those detected in NGC 3256.

Figure 1. Left panels: comparison of the absolute H-band magnitudes (from HST/NICMOS observations) of star clusters detected in the LIRG NGC 3256 and the starburst galaxy NGC 1530. We also show the typical magnitudes of globular clusters (see e.g., Kissler-Patig et al. 2002). Right panels: Hα luminosities of H II regions detected in LIRGs (NGC 3256 and Arp 299) and in normal galaxies. The arrow indicates the luminosity of 30 Dor, the prototypical giant H II region.

4. Giant H II Regions

In two previous studies we showed the presence of a population of bright H II regions in two LIRGs, Arp 299 (AAH00) and NGC 1614 (AAH01). A significant fraction of these H II regions displays Hα luminosities in excess of that of 30 Doradus, the prototypical giant H II region. The analysis of the sample of LIRGs in Table 1 has revealed that giant H II regions are ubiquitous in LIRGs and are located not only in and near the nuclei of interacting galaxies, but also at the interface of interacting galaxies and along the spiral arms of isolated systems.
In Fig. 1 (right panels) we compare the Hα luminosities (not corrected for extinction) of H II regions in LIRGs with those in a small sample of normal galaxies observed with the same spatial resolution from Alonso-Herrero & Knapen (2001). Giant H II regions (the luminosity of 30 Doradus is indicated with an arrow in Fig. 1) are more common in LIRGs than in normal galaxies. The measured sizes of giant H II regions in LIRGs when compared to those of normal galaxies rule out the possibility that these giant H II regions are just aggregations of “normal” H II regions. A more plausible explanation for this population of luminous H II regions in LIRGs is that regions of high gas pressure and density in LIRGs, ULIRGs, and interacting galaxies provide the necessary conditions for the formation of a large number of massive star (ionizing) clusters. Such extreme conditions are not likely to occur in normal galaxies.

5. Giant H II Regions and their relation to SSC: the age sequence

Despite the large numbers of near-IR SSCs and H II regions identified in LIRGs, there is only a small fraction of coincidences (4 – 30%) between H II regions and star clusters. We can use evolutionary synthesis models to reproduce the observed relative fractions of young and intermediate H II regions or clusters and old clusters in Arp 299 and NGC 3256. In Fig. 2 we show outputs of Starburst99 (Leitherer et al. 1999) for the time evolution of the absolute H-band magnitude and number of ionizing photons. We show two cluster masses and instantaneous star formation with a Salpeter IMF. For these assumptions and taking into account the detection limits for the complete distributions of H-band luminosities of clusters in NGC 3256 and Arp 299 we infer photometric masses for the detected clusters of between \( 5 \times 10^4 \) and \( 10^6 \) M\(_\odot\).

The fact that the peak of the H-band luminosity occurs after approximately 9 Myr, whereas at the same time the number of ionizing photons has dropped by about 2 orders of magnitude from the maximum, provides an explanation for the limited number of coincidences. Within the present detection limits in Arp 299 and NGC 3256, we can detect both H II region emission and a star cluster for the most massive clusters (\( \approx 10^6 \) M\(_\odot\)) only during the first 7 Myr (Fig. 2). The near-IR clusters with no detected H II region emission will be older than approximately 7 Myr. The H II regions with no detected cluster counterpart are most likely younger than 5 Myr, and have intermediate-mass (\( 5 \times 10^4 - 10^5 \) M\(_\odot\)) ionizing clusters. If, as observed in obscured Galactic H II regions, there are significant amounts of extinction during the first million years of the evolution of clusters and associated H II regions, then the observed fractions of H II regions and coincidences will be lower limits.

An estimate of the age distribution of the observed clusters can be inferred from the relative numbers of H II regions and near-IR star clusters and the model predictions: The higher the fraction of near-IR clusters compared to that of H II regions, the older the ages of the detected star clusters will be. The ages of the detected star clusters in Arp 299 and NGC 3256 range up to 20 – 40 Myr. Older clusters possibly created in this or previous episodes of star formation are likely to exist in these systems but cannot be identified with the present detection threshold. Another possibility to explain the apparent youth of the clusters in Arp 299 and NGC 3256 would be destruction of clusters. In that case, if the
Figure 2. The solid lines are outputs of Starburst99 (Leitherer et al. 1999) showing the time evolution of the number of ionizing photons ($\log N_{\text{Ly}}$, thin solid line, scale on the left hand side) and absolute H-band magnitude ($M_H$, thick solid line, scale on the right hand side) for a $10^6 M_\odot$ cluster (bottom panel) and a $10^5 M_\odot$ cluster (top panel), for an instantaneous burst, a Salpeter IMF (between 1 and 100 $M_\odot$) and solar metallicity. The dashed-dotted lines represent the approximate detection thresholds for NGC 3256: $M_H = -14$ mag and $\log N_{\text{Ly}} = 50.7 s^{-1}$. An H II region with no cluster counterpart will be the case when $\log N_{\text{Ly}}$ is above the detection threshold, but $M_H$ is not detectable yet (lightly hatched area). There will be a coincidence between an H II region and a near-IR star cluster when both $N_{\text{Ly}}$ and $M_H$ are above their respectively detection thresholds (closely hatched area). We will only observe a star cluster when $\log N_{\text{Ly}} < 50.7 s^{-1}$, but $M_H$ is still observable (cross-hatched area).
clusters have been created at a constant rate for the last 100 Myr, then roughly 50% of the clusters are destroyed during that time to account for the observed fraction of clusters in these two systems. The data presented in this paper does not allow us to distinguish between these two possibilities.

From the present observations and modeling we find that a large fraction of the youngest clusters (that is, the ionizing clusters of the H\textsuperscript{II} regions with ages less than 5 – 6 Myr) will not be detected from near-IR continuum imaging alone, as only some 8%–16% of these H\textsuperscript{II} regions in our sample of LIRGs appear to have near-IR cluster counterparts. This suggests that studies of the young star clusters in galaxies performed using only near-IR continuum imaging may be missing a significant fraction of the youngest star-forming regions.

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Discussion

J. M. Mas-Hesse: The peak in H-band emission predicted by evolutionary synthesis models at around 10 Myr is due to the formation of Red Supergiants. Predictions for RSGs are very much model-dependent, since they are strongly affected by rotation, so that they have to be taken with care.

A. Alonso-Herrero: Yes, I’m aware of this problem and obviously some of the results I’ve presented are model-dependent.

G. Tenorio-Tagle: Can you please indicate the physical size of the SSCs.

A. Alonso-Herrero: The sizes of the super star clusters are somewhat dependent on the spatial resolution (i.e., the distance of the galaxy). For the closest galaxies in our sample the typical diameters are of the order of 20 – 30 pc.