Intense Star Formation in Nearby Merger Galaxies

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Frontier Area 3: The Galactic Neighborhood (GAN)

Goal: Characterize the formation and evolution of massive star clusters in merger galaxies

- *What are the characteristics of massive star formation in mergers?*
- *How does starburst evolution relate to the evolutionary stage of mergers?*
- *How do supernova remnants evolve in very high-density environments?*

Arp 220 western nucleus (Parra et al. 2007)

Abstract

Currently accepted models of hierarchical galaxy formation posit that the most massive galaxies form from multiple mergers of smaller galaxies at relatively high redshift. To understand observations of forming galaxies at high redshift, we need much better understanding of star formation in the extreme environments of nearby merger galaxies. Telescopes already under construction, together with new instrumentation that can be on line in the next decade, will enable us to study these objects in detail. We propose detailed studies of the super star clusters that may dominate the energy output from these mergers, from the birth of massive stars to their death in supernovae, to understand the observational characteristics of forming galaxies at high redshift.

1. Introduction

Massive galaxies are thought to be built up hierarchically from multiple galaxy mergers at high redshift, as shown in the disturbed morphologies of galaxies seen in deep optical and infrared surveys (Ferguson et Ag. 2000; Giavalisco et Ag. 2004; Scoville et al. 2007). These mergers induced massive star formation at rates of 10^2–$10^3 M_\odot$ yr^{-1}, and the star formation in turn drove the evolution of the early galaxies. Understanding the universe we live in today thus depends critically on the detailed astrophysics of the star-formation in mergers. Present-day analogs of the early mergers are found among the highly obscured Luminous and Ultraluminous Infrared Galaxies. This white paper discusses the importance of very high sensitivity imaging of the nearby mergers at 10 milliarcsecond resolution or better, from sub-millimeter to centimeter wavelengths, in order to understand the galaxy formation processes.

2. Radio Properties of Nearby Starburst and Merger Galaxies

The prototypical nearby starburst galaxies are M82 and NGC 253. At their distances of $\sim$ 3 Mpc, the best available radio resolution of $\sim$0.″1 (1.5 pc) reaches to the scale of dense star clusters and supernova remnants (e.g., Ulvestad & Antonucci 1997; Muxlow et al. 1994). Extreme conditions also exist locally in dwarf galaxies such as He 2-10 (Johnson & Kobulnicky 2003) and NGC 5253 (Turner & Beck 2004), both at $<$ 10 Mpc, where most star formation is concentrated in a few extremely dense clumps. Such objects contain optically thick thermal radio sources powered by highly embedded super star clusters (SSCs) with radii of a few parsecs, ages of a few Myr, and containing a few thousand O stars. The SSCs are offset from the optical peaks, but coincide with infrared peaks that represent the natal material from which the clusters form. Studies of such regions with present and future telescopes are summarized by Johnson (2004) and Turner (2008).

Star formation rates of only a few solar masses per year imply that the nearby starbursts are poor proxies for distant mergers with star formation rates 100 times higher. Nearby major merger galaxies are better local analogs to high-z star-forming galaxies. The closest of these is the famous "Antennae" (NGC 4038/9) at 20 Mpc distance (Whitmore et al. 1999); other examples are Arp 299/NGC 3690 (Alonso-Herrero et al. 2000) and Arp 220 (Soifer et al. 1999). Multi-wavelength images reveal merging galaxy disks, galaxy nuclei separated by hundreds to thousands of parsecs, long tidal tails, and powerful infrared and molecular-gas emission. In the Antennae, HST imaging identified several thousand SSCs, with effective radii ranging up to ~ 10 pc (Whitmore et al. 1999). However, even in this apparently extreme case, the star-formation rate is only $20 M_{\odot}$ yr^{-1} (Zhang et al. 2001). To reach star-formation rates of over $100 M_{\odot}$ yr^{-1}, one must study somewhat more distant mergers such as Arp 299 (41 Mpc) and Arp 220 (77 Mpc). At their distances, $0\farcs1$ resolution is inadequate for SSCs, since it corresponds to linear scales of 20–40 pc.

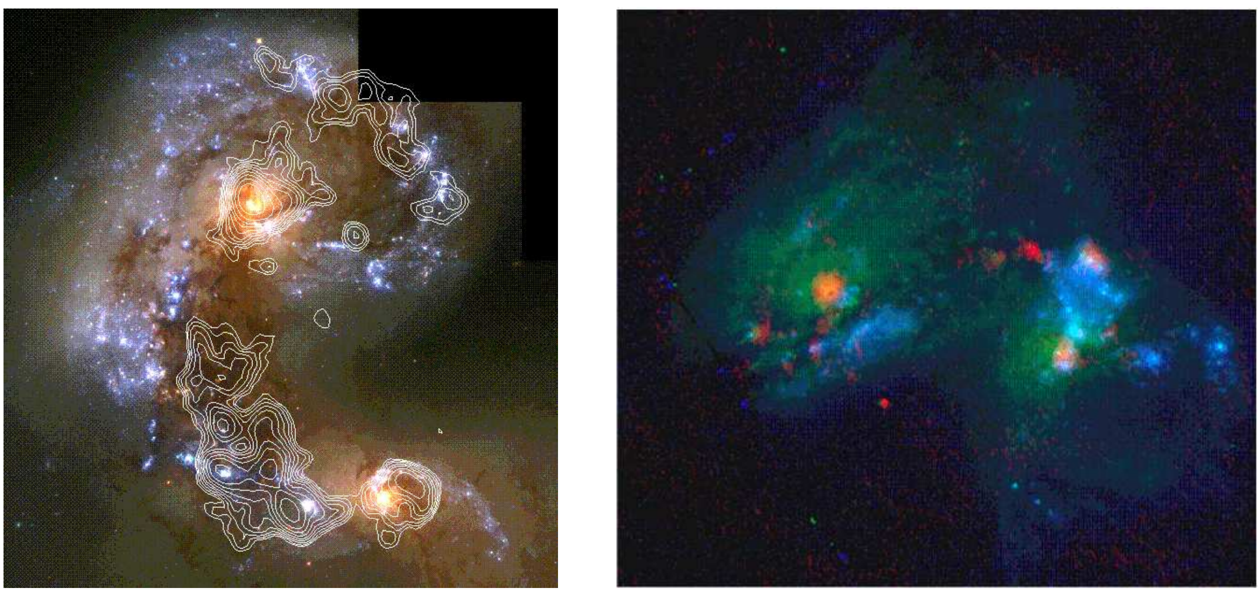

Fig. 1. Left: Composite optical (Whitmore et al. 1999) and CO (Wilson et al. 2000) image of the nearest merger, the Antennae, $2'$ (12 kpc) on a side. **Right:** Composite 250 nm (blue), 812 nm (green), and 6 cm (red) image of Arp 299, $50''$ (10 kpc) on a side. Images at 250 nm and 812 nm from Alonso-Herrero et al. (2000); radio image from Neff et al. (2004).

In all the nearby mergers, the optical emission is offset from the molecular, infrared, and continuum radio emission (see Figure 1); this longer-wavelength emission traces the densest star-forming regions. Hence, images from centimeter to sub-millimeter wavelengths are critical for elucidating the properties of these regions, and resolution well below $0\farcs1$ (100 milliarcseconds) is required to probe the SSC scales of a few parsecs or less.

3. Star Formation in High-Density Environments in Mergers

Our primary goal is to characterize the formation and evolution of massive star clusters in merger galaxies, which can be applied to understand the observed properties of galaxies at high redshift. The key element is the study of star formation in heavily obscured regions. Extinctions are substantial in starbursts even in the near-infrared (Ho et al. 1990). Radio continuum and radio recombination lines are impervious to extinction, and give solid estimates of the locations of massive stars and their numbers, through the Lyman continuum rates. The crucial area of the spectrum is the microwave, from 1 cm to 1 mm, where free-free emission peaks relative to synchrotron and dust emission.

3.1 What are the characteristics of massive star formation in mergers?

Rapid formation of massive stars in merger galaxies appears to be dominated by formation in SSCs a few parsecs in radius. We summarize some SSC properties in Table 1 (adapted from Turner 2008). Such basic quantities as the initial mass function and the efficiency of star formation (hence the total stellar mass) are poorly constrained in such environments. Images of dust and molecular gas at millimeter and sub-millimeter wavelengths can locate "proto-SSCs," and indicate whether they form from multiple cores in supergiant molecular clouds or from giant molecular clouds that collapse to form single SSCs (see Wilson et al. 2003). SSC gas content can be quantified by using mm/sub-mm molecular line (e.g., CO and HCN) and dust emission, as well as ionized gas emission at wavelengths near 1 cm; studies of the ionized gas emission and centimeter-wavelength recombination lines also yield the ionizing photon content, gas pressures, and kinematics. Combining the gas and dust measurements yields stellar and gas masses, hence star-formation efficiency. Radiation-transfer models also are needed, since the harsh environment of natal SSCs may significantly affect emission line strengths.

Table 1. Super Star Clusters in Context

Type	N_*	Mass ($M_\odot$)	d_h (pc)	ρ_h ($M_\odot \mathrm{pc}^{-3}$)	Age (yrs)
Globular cluster	$> 10^5$	$10^{3.5} - 10^6$	0.6–8	$10^{-1} - 10^{4.5}$	$> 10^9$
Embedded cluster	35–2000	350–1100	0.6–2	1–5	$10^6 - 10^7$
SSC	$> 10^5$	$10^5 - 10^6$	6–10	$\sim 10^4$	$10^6 - 10^7$

Note: N_* is the number of cluster members, d_h is the half-light diameter of the cluster, and ρ_h is the mean density inside the region containing half of the cluster mass.

Both ALMA and EVLA will provide access to a wealth of diagnostic tools, but modeling the star formation in SSCs requires observations having several resolution elements across the SSCs. For an 8–10 pc diameter SSC at 80 Mpc distance (Arp 220), the required 2–3 pc resolution corresponds to 5–8 milliarcseconds. This is a factor of two better resolution than available for ALMA at 1 mm, and a factor of 10 better than for EVLA at 1 cm. At 80 Mpc, the strongest thermal-emitting SSC in NGC 253 would be detectable (5σ) in 12 hours with EVLA at 1 cm; this source is 1–2 orders of magnitude less powerful than the SSCs seen in mergers and even in some nearby star-forming dwarfs. Heretofore, sensitivity and correlator capability have limited high-resolution studies of radio recombination lines in SSCs; although the EVLA correlator will improve sensitivity and spectral resolution by stacking multiple recombination lines, more collecting area is still critical. ALMA will have the sensitivity to detect the dust in the same objects. Thus, the key missing element is higher resolution in interferometers with the sensitivity of ALMA and EVLA, followed by added collecting area for EVLA.

3.2 How does starburst evolution relate to the evolutionary stage of mergers?

The SSCs in NGC 4038/9 are spread throughout the interacting disks (Whitmore et al. 1999), but the locations of radio supernovae and supernova remnants in Arp 220 (Lonsdale et al. 2006) may be evidence that the SSCs are concentrated in the nuclei in that later-stage merger. Although the locations of the SSCs are different, we do not understand how the star formation differs. Mid-infrared spectroscopy (e.g., JWST) can provide some insight into the physical conditions of the SSCs, but the results do not have a unique interpretation due to the low spatial resolution. For studying SSC properties along the merger sequence, we need to isolate SSCs at distances out to 200 Mpc, providing access to more than a dozen mergers at different stages. Isolating these SSCs (but not resolving them internally) requires 10 pc resolution, corresponding to 10 milliarcseconds.

3.3 How do supernova remnants evolve in very high-density environments?

As stars in SSCs reach ages of 3 Myr, they go supernova in large numbers. The selection effects mandated by obscuration mean that the known optical supernovae avoid the youngest and most massive SSCs. Hence young radio supernovae (RSNe) and supernova remnants (SNRs) are the signposts for locations of SSCs in the 3–10 Myr age regime, and may in fact be used to “count” the massive stars. In both Arp 220 (Lonsdale et al. 2006; Parra et al. 2007) and Arp 299 (Neff et al. 2004; Ulvestad 2009, in prep.), Very Long Baseline Inteferometry (VLBI) techniques reveal multiple RSNe and SNRs within a few parsecs of one another, probably within the same SSCs.

The understanding of SNR radio emission has broad applications. A key component of understanding radio emission from high-z galaxies is to understand the evolution of SNRs in SSC environments. Models exist for SNR evolution after breakout from their circumstellar shells (e.g., Chevalier et al. 2004), but these do not cover the case when SNRs begin to overlap. Do they overlap other SNRs while more powerful and younger than Cas A, and have their radio emission quenched by free expansion? Figure 2 shows radio powers of the SNRs in two mergers from the best VLBI imaging feasible with current instrumentation; observations of tens of hours can detect only sources more than 10 times the Cas A power. In order to reach conclusions about SNR evolution in dense environments, we must observe multiple SNRs within (at least) several SSCs. This requires a threshold near the Cas A power, to permit detection of a few hundred SNRs per merger. Thus the key requirement is a ten-fold increase in the sensitivity of long-baseline radio interferometers.

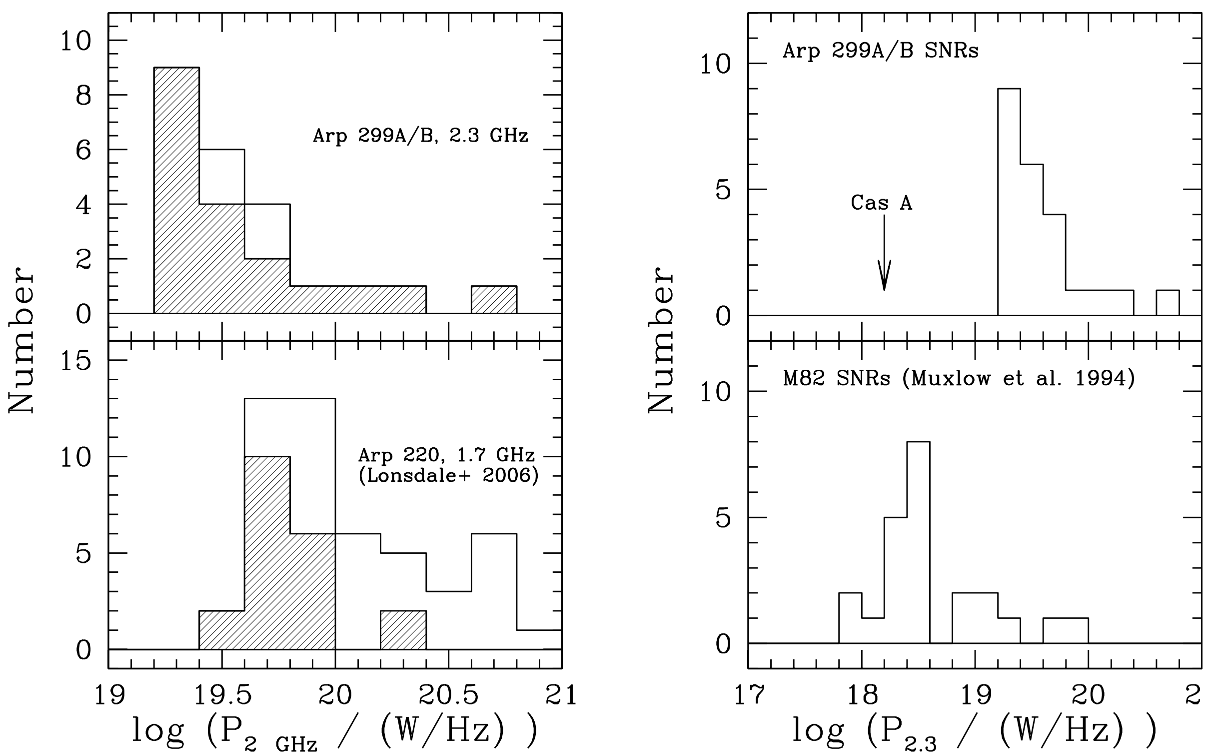

Fig. 2. **Left:** Radio luminosity functions of young SNRs in Arp 220 at 1.7 GHz and in Arp 299 at 2.3 GHz (Ulvestad 2009, in preparation). The two nuclei in each merger are distinguished by different shading. **Right:** Radio luminosity functions of young SNRs in Arp 299 (both nuclei combined, same data as left-hand panel) and M82. The Cas A power is indicated.

Star-formation rates at $z \approx 2$ and beyond are still quite uncertain–ultraviolet estimates are subject to large and unknown extinction corrections, so far-infrared and radio data may provide the least biased estimate. The EVLA will probe the sub-millijansky radio source population that is dominated by star formation (e.g., Condon 2007). Translating the newly measured radio flux densities into star-formation rates will require the improved understanding of SNR evolution discussed here.

4. Instrumental Requirements

The key instrumental requirements for our science goals have been indicated in Section 3. The ALMA telescope now under construction is adequate for studies of NGC 4038/9, but the baseline length needs to be increased to $\sim$ 30 km to resolve SSCs at $\sim$ 80 Mpc and to separate them at $\sim$ 200 Mpc.

At centimeter wavelengths, the primary requirements for merger studies are the following:

1. Factor-of-10 increase in resolution over EVLA at 1–4 cm wavelength to image the thermal emission from SSCs in mergers. This implies an additional collecting area comparable to EVLA (e.g., ∼120 12m antennas) on baselines out to a few hundred kilometers.

2. Factor-of-10 increase in sensitivity over current VLBI arrays at 3–20 cm wavelength in order to study the SNRs in mergers. This implies VLBI data rates increased to 10 gigabit s^{-1} (1.28 GHz bandwidth) as well as a moderate increase in collecting area (e.g., add the equivalent of 10 50m antennas at distances similar to the VLBA stations).

Many of the science goals outlined in this white paper can be achieved with a North America Array (see *http://www.nrao.edu/nio/naa/*) that expands and merges the EVLA and VLBA, but is considerably more modest than the Square Kilometer Array (SKA). Table 2 summarizes the centimeter-wavelength requirements compared to current and proposed radio interferometers, including the North America Array and SKA subsets that are most relevant to each problem.

Table 2. Centimeter-Wavelength Requirements and Comparisons

	Collecting Area (m^2)	Wavelength (cm)	Baselines (km)	Bandwidth (GHz)
SSCs (Sections 3.1 and 3.2):				
Requirement	1.5×10^4	1–4	40–400	8
EVLA (2012)	1.3×10^4	0.6–30	0.1–35	8
North America Array	1.3×10^4	0.6–30	40–400	8
SKA (post-2020)	$\sim 5 \times 10^4$	0.9–3	5–180	TBD
SNRs (Section 3.3):				
Requirement	2×10^4	2–20	100–5000	1.3
VLBA (2009)	5×10^3	0.7–21	240–8600	0.03
North America Array	2×10^4	0.6–30	200–8000	2
SKA (pre-2020)	$\sim 6 \times 10^4$	3–30	180–3000	2

Note: The typical VLBA bandwidth now is 32 MHz, but it will be 128 MHz within a year.

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