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Collision-Triggered Star Formation in the Antennae (NGC 4038/39)

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Abstract. New observations of the Antennae in CO emission reveal several extremely massive concentrations of molecular gas ($> 10^8$ $M_\odot$) that are gravitationally bound and well correlated with the bright 15 μm emission seen by the Infrared Space Observatory. Evidence for cloud-cloud collisions near the strongest 15 μm peak may provide an explanation for the unusually strong mid-infrared continuum emission in this region.

1. Introduction

At a distance of only 20 Mpc, the Antennae system (NGC 4038/39) is the closest example of a merger of two gas-rich spiral galaxies. Thus, the Antennae offer us a unique opportunity to study the effect of galaxy interactions on the star formation process. In addition, the Antennae have one of the largest known populations of super star clusters (Whitmore & Schweizer 1995) and are unusual in forming these super star clusters well outside the nuclei of the two galaxies. Infrared studies have revealed buried regions of massive star formation, with one region accounting for 25% of the mid-infrared luminosity of the entire system (Vigroux et al. 1996; Mirabel et al. 1998).

The physical and dynamical properties of the molecular interstellar medium can give us important clues to understanding the triggering of intense star formation in galaxy mergers. We have used the Caltech Millimeter Array to obtain new observations of the CO emission in the Antennae with a resolution of $3 \times 5''$ (300×500 pc). A comparison of these new CO data with the data from the Infrared Space Observatory (ISO) reveals intriguing evidence of cloud collisions near the brightest infrared region.

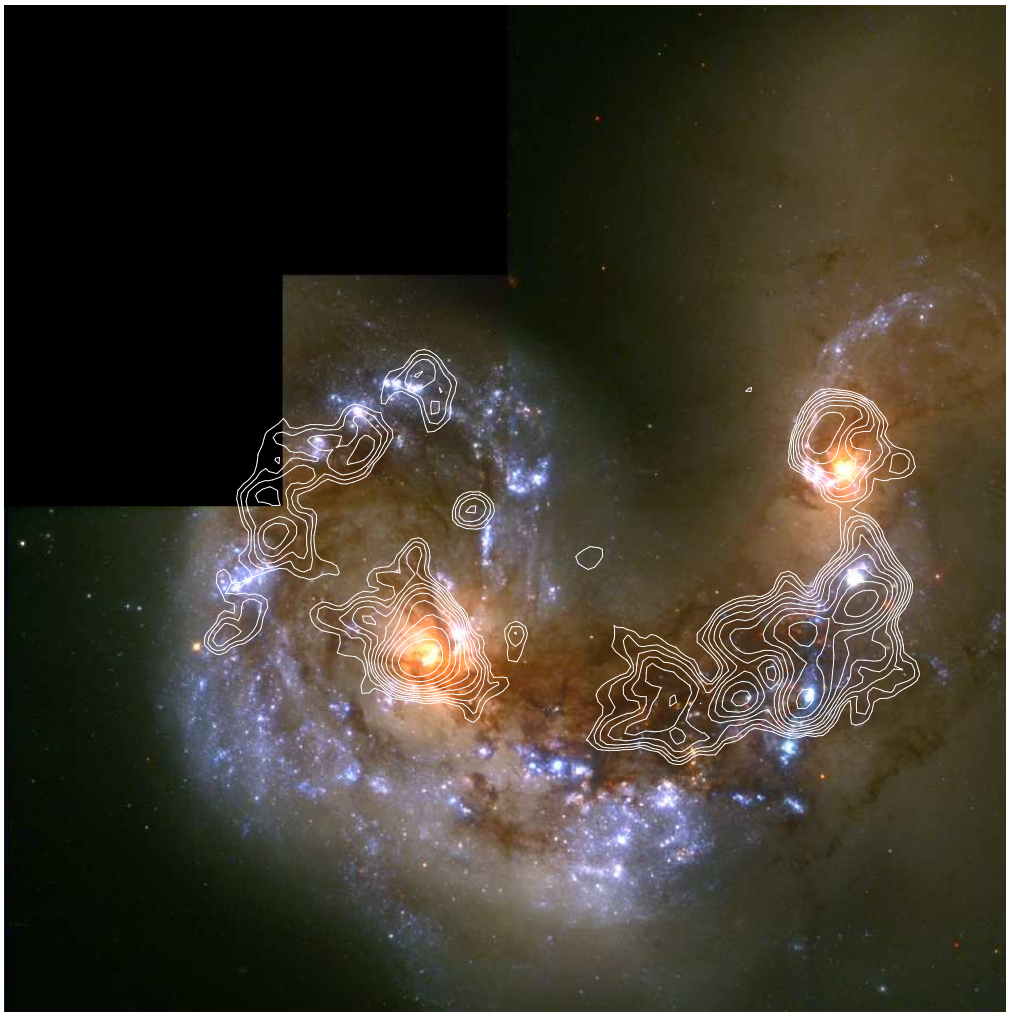

Figure 1. The CO integrated intensity map of the Antennae overlaid on an HST image (Whitmore et al. 1999; Wilson et al. 2000). North is towards the lower left corner and east is towards the lower right corner, approximately (see Wilson et al. 2000). The nucleus of NGC 4038 is the large, smooth CO concentration to the left of the picture and the nucleus of NGC 4039 is the large CO concentration in the upper right. The "overlap region", first identified by Stanford et al. (1990), is the extended, complex region of emission between the two nuclei. The contour levels are 1,1.6,2.5,4,6,9.5,15,23,37,57,90 Jy beam^{-1} km s^{-1}. The three brightest CO peaks in the overlap region are (from north to south) SGMC1, SGMC2, and SGMC3-5; these CO peaks also correspond to bright emission regions in the mid-infrared (Wilson et al. 2000; Vigroux et al. 1996; Mirabel et al. 1998; see also Figure 2).

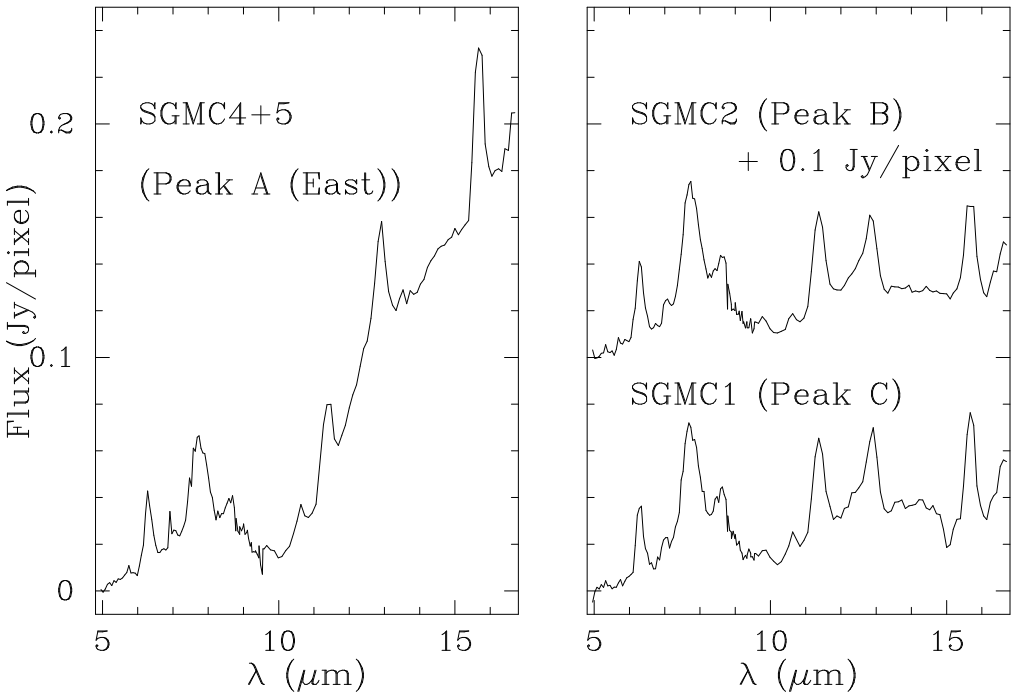

Figure 2. Mid-infrared spectra from ISO for the three strongest CO and 15 μm peaks (see also Vigroux et al. 1996; Mirabel et al. 1998).

2. Discussion

The largest molecular complexes in the map have molecular masses ranging from 1.4×10^8 $M_\odot$ to at least 5.5×10^9 $M_\odot$ (Wilson et al. 2000; see Figure 1). These complexes are significantly larger and more massive than giant molecular clouds in the Milky Way ($10^4 - 10^6$ $M_\odot$). They are also a factor of 5-10 times more massive than the giant molecular associations seen in the grand-design spiral galaxy M51 (Rand & Kulkarni 1990). Most of the complexes have molecular masses which are comparable to or larger than their virial masses, which implies that these complexes are gravitationally bound objects.

The three brightest CO peaks located in the "overlap region" (Figure 1) match up extremely well with the brightest infrared sources in this same region (Vigroux et al. 1996; Mirabel et al. 1998). Mid-infrared spectroscopy from ISO reveals that strong [NeII] and [NeIII] lines at 12.8 and 15.5 μm are seen towards all three regions (Figure 2). The strong [NeIII] lines in particular indicate the presence of massive O stars. However, strong mid-infrared *continuum* emission is only seen towards the brightest 15 μm peak. This strong continuum emission is likely due to very small dust grains heated to high temperatures by their close proximity to O stars. One possibility is that we are seeing the strongest mid-infrared peak when it is extremely young and has not yet had time to blow away its surrounding dust. However, this region is also unusual in that it contains three separate, massive ($> 10^8$ $M_\odot$) molecular complexes inside an area of just 1 kpc^2 (Figure 3), which suggests that cloud collisions may be an important

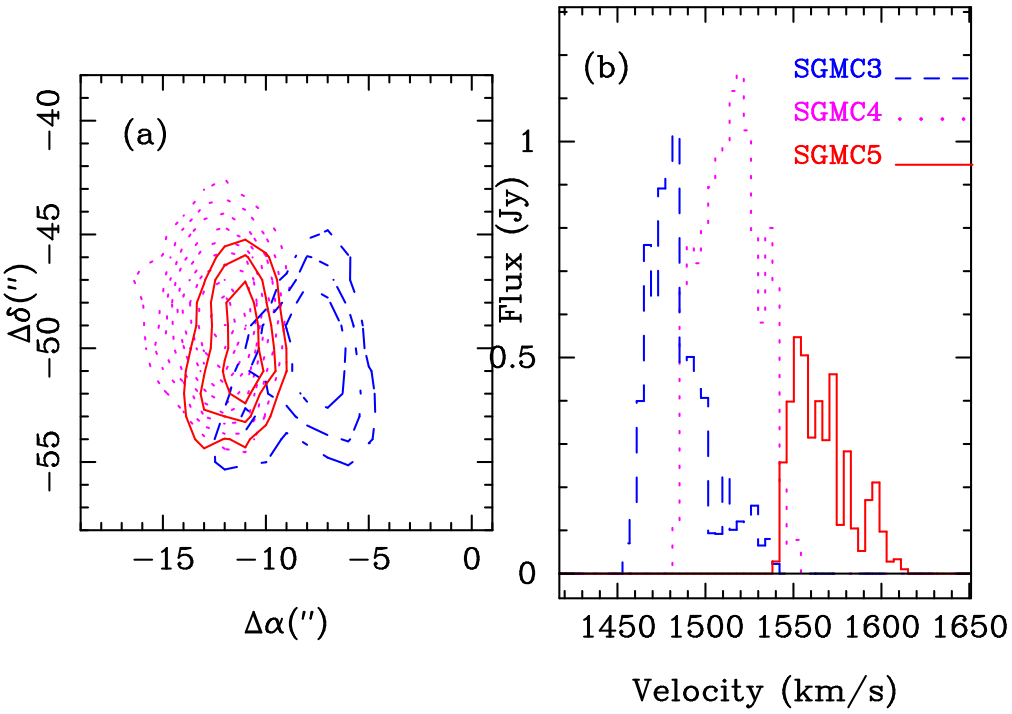

Figure 3. (a) Integrated intensity plots for the three individual super giant molecular clouds that make up the southern-most CO peak in overlap region of the Antennae. Contour levels are $(0.1, 0.2, 0.3, ...1) \times$ 39.6 Jy km s^{-1}. (b) Area-integrated spectra of the same three clouds. See Wilson et al. (2000) for details.

process in this region. Such collisions could continuously bring fresh supplies of very small dust grains into the sphere of influence of the massive stars, which would effectively provide the fuel for the strong continuum emission seen in the mid-infrared.

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