S23-90

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N91-14123

CO APERTURE SYNTHESIS OF NGC 4038/9 (ARP 244)

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ABSTRACT

We present high-resolution (~6") CO observations of the merging galaxies NGC 4038/9 made with the Owens Valley Millimeterwave Interferometer.

I. INTRODUCTION

Arp 244 comprises the two galaxies NGC 4038 and 4039. At a distance of 21 Mpc (V_{LSR}=1550 km s^{-1}, H_0=75 km s^{-1} Mpc^{-1}) this pair, popularly known as the Antennae, is the nearest example of merging disk galaxies. Previous observations of Arp 244 suggest the presence of several regions of active star formation, which could be due to the collision. Rubin, Ford, and D'Odorico (1970) observed many knots of Hα emission throughout both northern and southern galaxies. Most of these knots also show up as strong sources at 6 and 20 cm (Hummel and van der Hulst 1986). Single-dish CO data at one position between the two nuclei show $M(H_2)=2.6 \times 10^9 M_o$ (Sanders and Mirabel 1985). Finally, IRAS observations show the system to be moderately strong in the infrared, with L(40-400 μm)=$4.0 \times 10^{10} L_o$ compared to $L_B=2.9 \times 10^{10} L_o$.

II. OBSERVATIONS and RESULTS

The CO observations of Arp 244 were obtained between April and June 1988 using the OVRO Millimeter Wave Interferometer. Two fields with phase centers near the NGC 4039 nucleus and near the NGC 4038 nucleus were observed. The size of the synthesized beam is approximately 6.5" x 7" at PA=72°. The rms in a single cleaned channel map is 0.06 Jy $beam^{-1}$, corresponding to a brightness temperature of 0.12 K over the synthesized beam.

Contour maps of the integrated CO intensity for both interferometer fields are shown in Figure 1. Three CO concentrations are evident. Two are centered near the nuclei of NGC 4038 and NGC 4039, closely correlated with Hα and radio continuum maxima. A third CO emission region lies about 25" northeast of the NGC 4039 nucleus. A number of radio continuum, Hα, and 10 μm emission knots appear in this region. The total integrated intensity at the northern nuclear source, 302 K km s^{-1}, leads to a molecular mass of $8.3 \times 10^8 M_o$ assuming a Galactic CO to H_2 conversion factor of 3.0×10^{20} H_2 cm^{-2} (K km $s^{-1})^{-1}$. The integrated CO intensity of the southern nuclear source leads to a molecular mass of $2.4 \times 10^8 M_o$. The extranuclear CO concentration contains $1.2 \times 10^9 M_o$ of molecular gas, extending over 170 km s^{-1}, and is resolved in a number of channels. Its large size, mass, and morphology strongly suggest that it is an agglomeration of several clumps.

III. DISCUSSION

At the NGC 4038 nucleus the average surface density of molecular gas, $\sigma(H_2)$, is 470 M_o pc^{-2} over the source diameter of 1.5 kpc, and at the CO peak $\sigma(H_2)$ is 880 M_o pc^{-2}. In the NGC 4039 nucleus, the H_2 surface densitiy is 310 M_o pc^{-2} over the 1.3 kpc source. These densities are 2 - 4 times higher than in comparably sized regions at the nucleus of the Galaxy (Sanders, Solomon, and Scoville 1984), which could be due to the collision. The narrow velocity width (104 km s^{-1}) of the CO emission in the NGC 4038 nucleus is consistent with a relatively small inclination angle for the northern galaxy. The NGC 4039 nuclear source shows emission over a broader range of velocity (156 km s^{-1}) consistent with a larger inclination angle for the southern galaxy.

The high $\sigma(H_2)$ at both nuclei supports the view that the nuclear luminosity is due to intense star formation rather than nonstellar activity. The radio continuum source at the NGC 4038 nucleus is resolved at 20 cm. The nuclear source has a deconvolved half power size of 10" and a spectral index α=-0.62. Likewise, the radio continuum source at the NGC 4039 nucleus has a deconvolved half power size of 9" and α=-0.52. Hummel and van der Hulst (1986) estimated that for the NGC 4038 nucleus 10% of the total radio flux is thermal, and for the NGC 4039 nucleus 23% of the flux is thermal. These characteristics suggest that most of the radio emission is generated by HII regions and supernovae rather than by AGN.

A massive, ~1.2 x 10^9 M_o, concentration of molecular gas was detected about 3 kpc from the NGC 4039 nucleus in the region where the disks of the two galaxies overlap. The concentration comprises a number of distinct clumps in the channel maps; one each at the south, west, north and east sides of the extranuclear concentration. Several observations suggest that the gas in each of these clumps is actively forming stars. In the southern clump, a radio emission knot lies near the highest CO contour and has a relatively flat spectral index, -0.43, which implies 36% of the radio flux is thermal. Telesco and Bushouse (1989) report 10 μm detections at 4 pixels in an image taken with a 20 pixel array bolometer (1 pixel=4.5") centered on the southern clump, as shown by the crosses in Figure 1b. One other detection of 10 μm emission at the southern clump, from Wright *et al.* (1988), coincides with a strong Hα knot. The total 10 μm emission, coupled with the implied thermal radio flux and Hα emission for several sources in the southern clump, suggest that enhanced star formation exists in the southern clump. If we assume that the IR emission arises from dust heated by massive stars, we can estimate the current instantaneous rate of star formation in the southern clump of the extranuclear source following the method detailed in Hunter *et al.* (1986). Using the Salpeter IMF with an upper mass limit of 100 M_o and a lower mass limit of 0.1 M_o, we find a SFR of 4.1 M_o yr^{-1}. It is interesting to compare this with the SFR calculated from the observed Hα emission in the southern clump. Using the same assumptions, we calculate a SFR of 0.5 M_o yr^{-1} from the Hα emission. If we were to correct the observed Hα emission for the strong absorption expected in the clump then the two values would probably be in close agreement.

The other three clumps also show signs of active star formation. The radio knot at the western clump has a spectral index indicating about 10% of the emission at 20 cm to be of thermal origin. In the eastern clump, the radio knot has a spectral index which predicts a thermal to total flux density ratio of 1/3. Two Hα knots also lie at the same position as the eastern clump. Their observed flux may be used as above to calculate a SFR for this clump of 0.4 M_o yr^{-1}. This value is a lower limit because the Hα flux has not been corrected for absorption. At the northern clump there is only a weak region of Hα emission. No 10 μm data have yet been obtained for the northern, eastern and western clumps. The total SFR of the regions in the extranuclear source is about 5 M_o yr^{-1} based on the Hα and 10 μm data, as compared with ~5 M_o yr^{-1} for the entire Milky Way. However, these SFR estimates are uncertain because of possible variations in the IMF. Evolutionary synthesis studies of young stellar populations in interacting systems suggest that the IMF of a starburst may not be the same as the Salpeter law (Stanford and Code 1989). Careful calculation of an evolutionary synthesis fit to properly extinction-corrected multiwavelength data for the individual regions is necessary to draw meaningful conclusions about their SFR.

In Figure 2, the velocity contours of the southern field are shown. At the northern edge of the extranuclear source there appears to be a separate clump as can be seen from the velocity gradient between it and the bulk of the emission region to the south. The velocity range 1550 to 1590 km s^{-1} of this clump is more similar to the 1550 km s^{-1} velocity of an Hα knot in the southeastern part of NGC 4038 than to the velocities of 1451 km s^{-1} of the Hα knots in the northeastern part of NGC 4039. The implication is that this clump is associated with NGC 4038 and has collided with the larger clumps in the extranuclear CO source. The second interesting feature in Figure 2 is the gradient seen in the emission region at the nucleus in NGC 4039. This gradient suggests that the molecular gas is rotating about the nucleus. The increase in the velocity of the CO emission with distance from the 2.2 μm peak of the nucleus agrees with the velocites of the Hα emission knots in the same area. The sense of this rotation of the molecular gas in the NGC 4039 disk agrees with that of the stellar disk in the dynamical simulation of the collision by Barnes (1988).

One of us (SAS) thanks the Graduate School of the University of Wisconsin and the Organizing Committee of this conference for financial support enabling him to attend.

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Figure 1a (upper left). Integrated CO intensity map of the northern field. The velocity range is 1350 to 1750 km s^{-1}. Contour levels are 5, 10, 20, 30, 40, 50, 60, 70, 80, and 90 % of the peak flux of 79 Jy km s^{-1}/beam. A radio (Hummel and van der Hulst 1986) and Hα (Kennicutt and Keel 1989) knot is marked by a filled circle, and the 2.2 μm peak of NGC 4038 by an X.

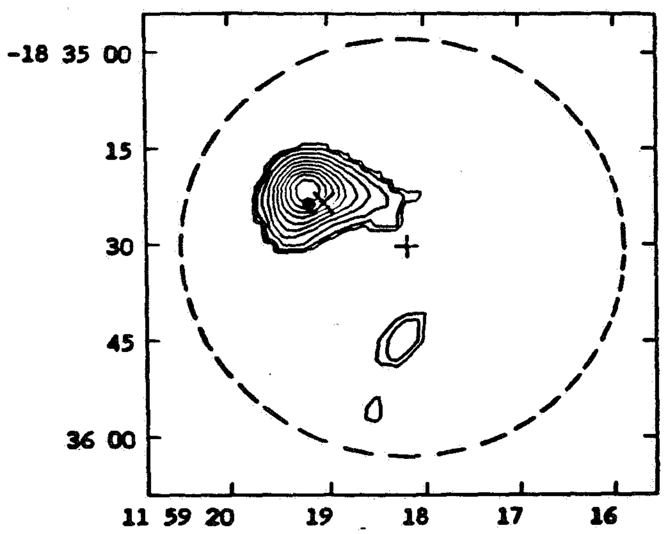

Figure 1b (lower left). Integrated CO intensity map of the northern field. The velocity range is 1350 to 1750 km s^{-1}. Contour levels are 5, 10, 20, 30, 40, 50, 60, 70, 80, and 90 % of the peak flux of 89 Jy km s^{-1}/beam. Radio/Hα knots and the 2.2 μm peak of NGC 4039 are marked by filled circles and an X, respectively. 10 μm detections (Telesco and Bushouse 1989; Wright *et al.* 1988) are represented by crosses whose size corresponds to the IR beam. In each map, the dahsed circl indicates the interferometer primary beam size, and a small cross the phase center.

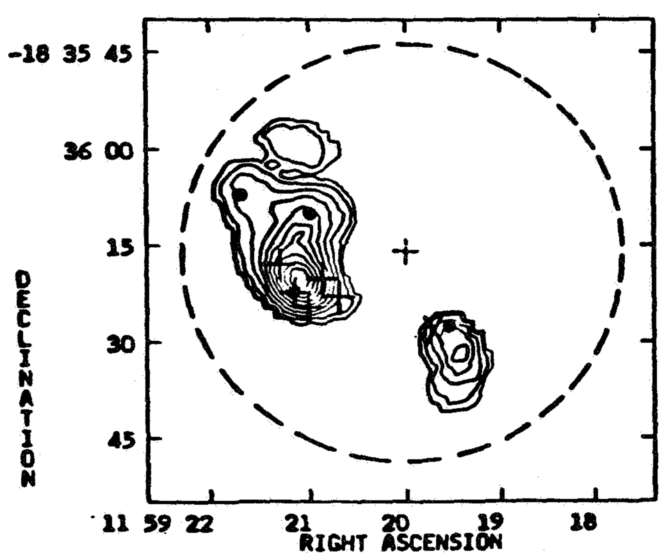

Figure 2 (lower right). A plot of CO velocity contours in the southern field. An X marks the position of the 2.2 μm peak of NGC 4039. The velocity of each contour is indicated.