THE DENSE MOLECULAR CORE OF ARP 220

SIMON J. E. RADFORD, J. DELANNOY, D. DOWNES, M. GUÉLIN,
S. GUILLOTEAU, A. GREVE, R. LUCAS, D. MORRIS, AND J. WINK
Institut de Radio Astronomie Millimétrique, Grenoble, France

ABSTRACT. Using the IRAM interferometer we have mapped HCN($1 \rightarrow 0$), HCO^+($1 \rightarrow 0$), and 3.5 mm continuum emission from Arp 220, the prototype infrared ultraluminous galaxy. The extended molecular emission and velocity gradient are aligned with the optical dust lane. The HCN and HCO^+ lines are exceptionally strong, suggesting a connection between the dense molecular gas they trace and Arp 220's enhanced infrared emission. The inferred gas density and filling factor imply the nucleus of Arp 220 may be a *giant* molecular cloud.

I. INTRODUCTION

IRAS observations revealed the peculiar galaxy Arp 220 has a far infrared luminosity of $10^{12}\,L_\odot$ and a far infrared-to-optical luminosity ratio of ≈ 100 (Soifer *et al.* 1984). It is a strong emitter of CO line emission and interferometric measurements show the bulk of the CO($1 \rightarrow 0$) emission comes from a very small region around Arp 220's nucleus (Scoville, this conference; Okamura, this conference). The total H_2 mass estimated from CO($2 \rightarrow 1$) and ($1 \rightarrow 0$) observations is $2.6 \times 10^{10}\,M_\odot$ (Radford, Solomon, and Downes 1990). Despite Arp 220's copious molecular component, its $L_{\rm FIR}/M(H_2)$ ratio is extremely high. Possible origins of this extreme luminosity are an intense star burst or an active nucleus.

To better determine the distribution of molecular gas in this unusual galaxy, we are carrying out millimeter measurements of several different spectral lines. Strong CS($3 \rightarrow 2$) emission from Arp 220 was detected by Solomon, Radford, and Downes (1990) with the IRAM 30 m telescope. Here we present interferometric observations of Arp 220's HCN($1 \rightarrow 0$), HCO^+($1 \rightarrow 0$), and $\lambda = 3.5$ mm continuum emission.

II. OBSERVATIONS AND RESULTS

We observed Arp 220 with four configurations of the three antenna IRAM interferometer on Plateau de Bure, France, between 1989 December and 1990 March, resulting in twelve baselines with projected lengths from 18 m to 280 m. The quasar 1502+106 was used as a phase calibrator and the flux scale was related through 3C 84 (11 Jy) to the single dish flux of W3(OH) (3.6 Jy) (Steppe *et al.* 1988). Arp 220 was observed twice in each configuration, once for each line. The lines were observed in the receivers' USB and the continuum flux in the LSB. Sideband separation, achieved by phase switching the receivers, was better

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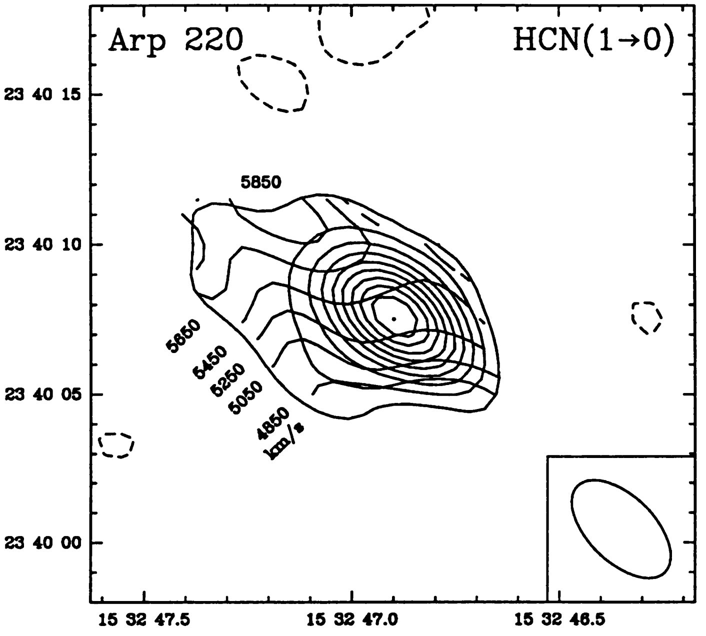

FIGURE 1. Integrated HCN($1\rightarrow 0$) emission from Arp 220 with velocity field superimposed. The flux contour increment is 3 Jy km s^{-1} beam^{-1} and the dashed contour is negative. Intensity weighted velocity contours are labeled by their LSR redshifts ($c\Delta\lambda/\lambda$) in km s^{-1}. The synthesized beam (insert) is 4.1″ x 2.2″ at a 45° position angle.

than 20 dB. A wideband correlator with ten 50 MHz subbands gave a velocity resolution of 172 km s^{-1}. Line emission maps were made from the difference between the the USB line + continuum visibilities and the corresponding LSB continuum visibilities. The maps were generated with natural weighting and then CLEANed. We have obtained comparison spectra with the IRAM 30 m telescope.

A map of velocity integrated HCN($1\rightarrow 0$) emission from Arp 220 is shown in Figure 1. The emission is more extended than the 4.1″×2.2″ beam. We estimate a deconvolved source size between 2″ and 3″, which corresponds to a linear size of 600 pc to 1 kpc. Superimposed on this map are intensity weighted velocity contours. A strong velocity gradient from NE from SW is apparent, probably due to rotation of the galaxy. Both the velocity gradient and the spatial extension of the HCN($1\rightarrow 0$) emission are roughly aligned with the dust lane present in optical images (Friedman, Jones, and Stein 1988). This suggests the molecular material is in a rotating disk seen edge-on.

The HCO^{+}($1\rightarrow 0$) emission appears somewhat more extended than the HCN($1\rightarrow 0$) emission, with a source size between 2″ and 4″. The total continuum flux is 35 mJy and from our maps we infer a source size of 1″ to 2″, consistent with the 1″ separation of the double nucleus seen at cm and IR wavelengths (Norris 1988; Graham *et al.* 1990). Table I

TABLE I. IRAM Interferometer Measurements of Arp 220.

Quantity	$HCN(1\rightarrow0)$	$HCO^+(1\rightarrow0)$
Total Flux ($Jy\,km\,s^{-1}$)	35	20
T_b (K)	0.6	0.2
L ($10^8\,K\,km\,s^{-1}\,pc^2$)	7	4
$CO(1\rightarrow0)$/line ratio	8	14

summarizes the results of our observations of Arp 220. Since individual molecular clouds are unresolved, the peak brightness temperatures are lower limits to the true brightness temperatures.

IV. DISCUSSION

Relative to $CO(1\rightarrow0)$, Arp 220's $HCN(1\rightarrow0)$ and $HCO^+(1\rightarrow0)$ lines are stronger than in other galaxies. For comparison, the $CO(1\rightarrow0)/HCN(1\rightarrow0)$ and $CO(1\rightarrow0)/HCO^+(1\rightarrow0)$ ratios averaged over the *whole* of Arp 220 are 8 and 14, respectively, less than they are in the centers of of M 82 and NGC 253 (Nguyen-Q-Rieu, Nakai, and Jackson 1988). HCN and HCO^+ line emission both trace denser gas [$\approx 10^4\,cm^{-3}$] than that traced by CO line emission. The strengths of these lines imply that not only does Arp 220 have a massive molecular component, but much of the gas is at high density. Arp 220's $L_{FIR}/M(H_2)$ ratio is much higher than ordinary galaxies, which suggests a connection between abundant high density molecular material and enhanced infrared luminosity.

A molecular mass-luminosity relationship may be derived for any tracer if the excitation conditions of the line can be estimated (Solomon, Radford, and Downes 1990). HCN emission comes predominantly from regions where the density is $\approx 10^4\,cm^{-3}$ and the kinetic temperature is likely to be about 50 K, somewhat warmer than regions of CO line emission. With these parameters, we find a mass of high density H_2 of about $10^{10}\,M_\odot$, similar to that estimated from the $CS(3\rightarrow2)$ line emission.

Combining this mass estimate with the source size we infer from the maps, we estimate the surface density of dense H_2 is $13000\,M_\odot\,pc^{-2}$. If the gas is in a uniform disk 200 pc thick, the *average* volume density of H_2 is $1300\,cm^{-3}$. A uniform sphere of 1 kpc diameter would have a volume density of $400\,cm^{-3}$. This implies the filling factor of dense molecular material may be 5 or 10%, and even larger for the more diffuse gas where the bulk of the CO line radiation is emitted.

Our results indicate the center of Arp 220 may be, indeed, essentially one *giant* molecular cloud. Rather than, or in addition to, a supermassive black hole at the center of Arp 220, it appears there is a supermassive molecular cloud.

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