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Variation of Molecular Line Ratios and Cloud Properties in the Arp 299 Galaxy Merger

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ABSTRACT

High resolution observations of $^{12}\text{CO}(2.''3)$, $^{13}\text{CO}(3.''9)$, and HCN ($5.''4$) $J=1-0$ in the galaxy merger Arp 299 (IC 694 and NGC 3690) show the line ratios vary dramatically across the system. The $^{12}\text{CO}/^{13}\text{CO}$ ratio is unusually large, 60 ± 15 , at the IC 694 nucleus, where ^{12}CO emission is very strong, and much smaller, 10 ± 3 , in the southern extended disk of that galaxy. Elsewhere, the $^{12}\text{CO}/^{13}\text{CO}$ line ratio is 5-20, typical of spiral galaxies. The line ratio variation in the overlap between the two galaxies is smaller, ranging from 10 ± 3 in the east to 20 ± 4 in the west.

The $^{12}\text{CO}/\text{HCN}$ line ratio also varies across Arp 299, although to a lesser degree. HCN emission is bright towards each galaxy nucleus and in the extranuclear region of active star formation; it was not detected in the IC 694 disk, or the eastern part of the overlap region, leading to lower limits of 25 and 20 respectively. By contrast, at the nuclei of IC 694 and NGC 3690 the ratios are 9 ± 1 and 14 ± 3 respectively. In the western part of the overlap region it is 11 ± 3 .

The large $^{12}\text{CO}/^{13}\text{CO}$ 1–0 intensity ratio at the nucleus of IC 694 can primarily be attributed to a low to moderate optical depth ($\tau \lesssim 1$) in the ^{12}CO 1–0 line. These data support the hypothesis that unusually high $^{12}\text{CO}/^{13}\text{CO}$ line ratios (> 20) are associated with extremely compact molecular distributions in the nuclei of merging galaxies. Relative to ^{12}CO , ^{13}CO 1–0 is brightest in quiescent regions of low ^{12}CO surface brightness and weakest in starburst regions and the galactic nuclei. A medium consisting of dense ($n = 10^4 - 10^5 \text{ cm}^{-3}$) and warm ($T_k > 50 \text{ K}$) gas will reproduce the extreme line ratios observed in the nucleus of IC 694, where the area filling factor must be at least 20%.

Subject headings: galaxies: evolution — galaxies: individual(Arp 299) —
galaxies: ISM — galaxies: starburst — radio lines: galaxies — radio lines: ISM

1. Introduction

The inner kiloparsecs of starburst and interacting galaxies harbor stunning amounts of molecular gas, $10^9 - 10^{10} M_{\odot}$ (e.g., Scoville *et al.* 1991; Bryant & Scoville 1996). In these environments, molecular clouds are subject to intense radiation fields, supernovae explosions, winds from newborn hot stars, strong tidal forces, and gas surface densities several order of magnitudes higher than in the Milky Way disk. These are also extremely active star formation sites. Knowledge of the physical conditions and structure of molecular gas in interacting systems is essential to understand the starburst activity and its role in galaxy evolution.

Arp 299 is an IR-luminous ($L_{\text{IR}} \approx 8 \times 10^{11} L_{\odot}$) merger system of two galaxies, IC 694 and NGC 3690. Strong ^{12}CO emission has been detected from the nuclei of IC 694 and NGC 3690 and from the interface between the two galaxies (Solomon & Sage 1988; Casoli *et al.* 1989; Sargent *et al.* 1987; Sargent & Scoville 1991). The two nuclei, as well as the western overlap region, currently harbor intense star formation activity (c.f., Gehrz *et al.* 1983; Baan & Haschick 1990). Furthermore, the nucleus of IC 694 is a flat-spectrum radio source, and may be an AGN (Gehrz *et al.* 1983).

Lower resolution (single dish) observations reveal an unusually large $^{12}\text{CO}/^{13}\text{CO}$ 1–0 line intensity ratio, $\gtrsim 20$ in Arp 299 (Aalto *et al.* 1991; Casoli *et al.* 1992). These observations left it unclear whether this is due to weak ^{13}CO in the whole system or to a varying $^{12}\text{CO}/^{13}\text{CO}$ 1–0 line ratio. Observations at $20''$ and $11''$ resolution by Casoli *et al.* (1992) suggest little variation in the $^{12}\text{CO}/^{13}\text{CO}$ 1–0 line ratio and none in the $^{12}\text{CO}/^{13}\text{CO}$ 2–1 line ratio. In contrast, Aalto *et al.* (1995) note substantial variations at $28''$ resolution in the $^{12}\text{CO}/^{13}\text{CO}$ 2–1 ratio: the ratio is about 17 in IC 694; close to 9 in NGC 3690; and about 7 in the interface region between the two disks. Solomon *et al.* (1992) detected bright HCN emission in $28''$ maps of Arp 299. They measured $^{12}\text{CO}/\text{HCN}$ ratios of 11 in

IC 694 and 13 in the interface region.

2. Observations and Results

Aperture synthesis ^{12}CO , ^{13}CO , and HCN 1–0 mapping of Arp 299 was carried out with the Owens Valley Radio Observatory (OVRO) millimeter array between March, 1995, and February, 1996. SIS receivers on the six 10.4 m telescopes provided typical system temperatures (SSB) of 600 K, 450 K, and 350 K for ^{12}CO , ^{13}CO , and HCN. Quasars 1150+497 and 0917+449 were used for phase calibration and Uranus and Neptune for absolute flux calibration. The synthesised beams are $2.''5 \times 2.''2$ for ^{12}CO (uniform weighting), $4.''3 \times 3.''6$ for ^{13}CO (natural weighting), and $5.''6 \times 5.''3$ for HCN (natural weighting). At 2.6 mm wavelength with $2.''3$ resolution, a brightness temperature of 1 K corresponds to 57 mJy beam^{-1} . The digital correlator, centered at $V_{\text{LSR}} = 3100 \text{ km s}^{-1}$, provided a total velocity coverage of 1123 km s^{-1} for ^{12}CO , 1175 km s^{-1} for ^{13}CO , and 1407 km s^{-1} for HCN. Data were binned to 4 MHz resolution, corresponding to 10 km s^{-1} for ^{12}CO and ^{13}CO and 13 km s^{-1} for HCN. At 110 GHz an unresolved continuum source of $17 \pm 2 \text{ mJy}$ was detected in the center of IC 694. Continuum emission was also detected in NGC 3690 ($5 \pm 2 \text{ mJy}$) and the overlap region ($9 \pm 2 \text{ mJy}$). We subtracted this continuum emission from the line emission before maps were made.

The main structures found by Sargent & Scoville (1991) with the three telescopes array are recovered in our new ^{12}CO map (Figure 1a), but our increased uv coverage enable improved deconvolution. Lower surface brightness emission (A2), possibly a molecular disk or bar, extends 10–15'' southeast of the IC 694 nucleus (A1), coincident with the remnant optical disk. The center of NGC 3690 (B1) is also surrounded by weak, extended emission (B2 and B3) with a somewhat S-shaped morphology. Where the two galaxies overlap, three distinctive clumps (C1, C2, and C3) can now be discerned. Weaker, extended emission is

also recovered better in our new ^{12}CO map and clumpy structures can be distinguished at the center of the map (F). These structures appear to connect the major components A, B, and C. In addition, there is a clump (D) north of the main features with systemic velocity $\approx 3280 \text{ km s}^{-1}$, which is beyond the bandwidth of the earlier OVRO data.

Bright 6 cm radio continuum peaks at the nuclei of IC 694 and NGC 3690 (Gehrz *et al.* 1983; Condon *et al.* 1991) coincide with the ^{12}CO peaks to within the estimated positional uncertainty ($0.''5$). There is also reasonable positional agreement between the two brightest ^{12}CO clumps in the overlap region (C) and two additional 6 cm radio continuum peaks: C1 and the western radio continuum peak are also coincident within $0.''5$, although the discrepancy between C2 and the eastern radio continuum peak is somewhat larger, $\Delta\alpha = 0.''8$. Weaker radio continuum emission at 18 cm and 6 cm is spatially coincident with the extended ^{12}CO emission in regions A2, B2, B3, and F (Baan & Haschick 1990; Gehrz *et al.* 1983).

The velocity field image (Figure 2, Plate 1) reveals a monotonic shift from the blueshifted emission from A2 in IC 694 to redshifted emission from the overlap region C and from region D. Velocity gradients within C and D are small. The velocity field of NGC 3690 is complicated by a double-peaked emission structure of B2, and both B2 and B3 appear blueshifted relative to the center, B1.

The nuclei of both IC 694 (A1) and NGC 3690 (B1) remain unresolved by our $2.''2$ synthesised beam. A two-dimensional Gaussian fit to the nuclear emission of IC 694 and NGC 3690 yields upper limits to the source diameters of $1.''4$ and $1.''5$, corresponding to radii of 140 and 150 pc, respectively (for $D=42 \text{ Mpc}$). This implies a lower limit of 18 K to the ^{12}CO brightness temperature in the IC 694 nucleus, and therefore, the cloud filling factor is quite high in the inner 200 pc. Even if the intrinsic brightness temperature is as high as 100 K, the surface filling factor of clouds is still almost 20%. The three features in

the overlap region are resolved, with sizes of 792×322 pc (C1), 876×428 pc (C2), and 684×456 pc (C3). Derived properties for all designated regions are presented in Table 1.

The total molecular mass of Arp 299, estimated from $M(\text{H}_2) = 1.2 \times 10^4 S\Delta v D^2 M_\odot$ (D is the distance in Mpc; $S\Delta v$ is the integrated ^{12}CO 1–0 line flux in Jy K kms^{-1}), is $7.5 \times 10^9 M_\odot$, 87% of the value estimated by Solomon and Sage (1988) from their single dish map. This formula corresponds to $N(\text{H}_2)/I(^{12}\text{CO})=3 \times 10^{20} \text{ cm}^{-2} (\text{K km s}^{-1})^{-1}$ (Sargent & Scoville 1991), a standard Galactic ^{12}CO luminosity to H_2 mass ratio. The conversion factor may vary, however, across Arp 299, since the line ratios indicate different cloud properties.

The most striking feature of the ^{13}CO 1–0 map (Figure 1b) is the *absence of strong emission at the nucleus of IC 694 (A1)*. Emission is detected in the A2 region of IC 694, in the overlap region C, and in NGC 3690. Unlike Casoli *et al.* (1992) we find significant variation in the $^{12}\text{CO}/^{13}\text{CO}$ 1–0 line ratio across Arp 299. From the very high value of 60 ± 15 at the IC 694 nucleus (A1) the ratio drops to 10 ± 3 in the A2 region. The global ratio for NGC 3690 is 13 ± 2 , but there is an indication that the ratio is higher in the nucleus, B1, than in B2 or B3. The ratio for the east (C3) and west (C1) overlap region is 11 ± 3 and 20 ± 4 respectively. The spatial correlation between the ^{13}CO emission and radio continuum emission peaks is also poor.

As for ^{12}CO , the HCN map (Figure 1c) is dominated by a peak at the center of IC 694 (A1), where the $^{12}\text{CO}/\text{HCN}$ line ratio is 9 ± 1 . Emission is also detected at the nucleus of NGC 3690, where the ratio is 14 ± 3 , and in the western (C1) overlap region, where $^{12}\text{CO}/\text{HCN}= 11 \pm 3$. There is very little HCN in regions A2 and C3. The HCN and ^{13}CO line emission peaks appear anticorrelated.

3. The molecular line-ratios

As a system, Arp 299 is not deficient in ^{13}CO . In all regions but the core of IC 694, we observe $^{12}\text{CO}/^{13}\text{CO}$ line ratios typical of star forming regions in other galaxies (e.g., Aalto *et al.* 1995, 1991; Young & Sanders 1986; Rickard & Blitz 1985). Relative to ^{12}CO , ^{13}CO 1–0 is brightest in quiescent regions of low ^{12}CO surface brightness, and weak in starburst regions and galactic nuclei. In contrast, HCN 1–0, like ^{12}CO , is bright in the two galaxy centers and in regions of active star formation. These line ratio variations are, most likely, caused by differences in line excitation. Our results support the suggestion (Aalto *et al.* 1995) that *unusually* high (i.e. > 20) $^{12}\text{CO}/^{13}\text{CO}$ 1–0 line ratios tend to be associated with extremely compact molecular distributions centered on the nuclei of merging galaxies and are primarily due to a small or moderate optical depth, $\tau \lesssim 1$, in the ^{12}CO 1–0 line. High ambient pressures, strong tidal forces and ongoing starburst or AGN activity lead to substantial changes in cloud structure and physical conditions. Bryant (1996) also finds that HCN 1–0 is bright in regions of high ^{12}CO surface brightness in merging galaxies.

3.1. IC 694

The line ratio variation from the IC 694 disk, where $^{12}\text{CO}/^{13}\text{CO} = 10$ and $^{12}\text{CO}/\text{HCN} \gtrsim 25$, to its nucleus, where the corresponding values are 60 and 9, reflects a dramatic change in cloud properties.

The bright HCN line accompanied by relatively weak ^{13}CO emission ($\text{HCN}/^{13}\text{CO} = 7 \pm 2$) implies a population of unusually dense and warm clouds. The HCN 1–0 strength implies densities $n \gtrsim 10^4 \text{ cm}^{-3}$ if the HCN excitation is dominated by collisions with H_2 . It is also likely that the density is $\lesssim 10^5$, so that most of the HCN population will remain in the lower levels and $\tau_{10} > 1$. At these densities, the ^{12}CO and ^{13}CO 1–0 transitions

are thermalised. If the kinetic temperature is also high, the lower levels may become significantly depopulated, effectively reducing the optical depth of the 1–0 line. Then the ^{13}CO 2–1/1–0 line ratio should be > 1 . Comparing the single dish ^{13}CO 2–1 flux (Aalto *et al.* 1995) with our ^{13}CO 1–0 flux from the nucleus of IC 694, we estimate ^{13}CO 2–1/1–0 $\gtrsim 2$, implying that the gas temperature is high, > 50 K. Although the single dish beam was large, $28''$, the bulk ($\gtrsim 65\%$) of the ^{12}CO 2–1 emission within the beam originates in the nucleus of IC 694 (A1).

Since the lower transitions of ^{12}CO and ^{13}CO appear thermalised, LTE can be assumed to estimate the ^{12}CO column density, $N(^{12}\text{CO})$. We find it unlikely that the $^{12}\text{CO}/^{13}\text{CO}$ abundance ratio is extremely high (section 3.3). Therefore, a high $^{12}\text{CO}/^{13}\text{CO}$ 1–0 line ratio indicates a low to moderate optical depth ($\tau \lesssim 1$) in the ^{12}CO 1–0 line. The high intrinsic ^{12}CO 1–0 brightness temperature makes $\tau \ll 1$ unlikely, and we therefore assume $\tau_{10}(^{12}\text{CO}) \approx 1$. The optical depth of the 1–0 transition can be expressed as $\tau_{10}(^{12}\text{CO}) \approx 3.9 \times 10^{-15} N(^{12}\text{CO})(1 - e^{-5.53/T_{\text{ex}}})/T_{\text{ex}}\Delta V$. For a temperature $T_{\text{ex}}=100$ K, line width $\Delta V = 5 \text{ km s}^{-1}$, and $\tau_{10}=1$, the ^{12}CO column density $N(^{12}\text{CO}) = 2 \times 10^{18} \text{ cm}^{-2}$ (per cloud) and the resulting brightness temperature $T_B(^{12}\text{CO}) \approx 60$ K. For a density of $n = 10^4 \text{ cm}^{-3}$ and a ^{12}CO abundance, $[^{12}\text{CO}/\text{H}_2]=5 \times 10^{-5}$, the cloud radius $r = N(^{12}\text{CO})/2x(^{12}\text{CO})n(\text{H}_2)=0.7 \text{ pc}$ — not unlike cores or clumps within Giant Molecular Clouds in the Galaxy. At this gas density, HCN is not thermalised so $T_{\text{ex}}(\text{HCN})$ for the 1–0 line will be significantly lower than that for ^{12}CO . If the abundance ratio $[^{12}\text{CO}/\text{HCN}] \approx 10^3$, then $\tau_{10}(\text{HCN})$ is an order of magnitude higher than $\tau_{10}(^{12}\text{CO})$. The resulting $T_B(\text{HCN})$ is sufficiently high to account for a $^{12}\text{CO}/\text{HCN}$ line ratio of 9.

Above, we infer a clumpy molecular medium because we chose a $\Delta V = 5 \text{ km s}^{-1}$, yielding small clouds with $r < 1 \text{ pc}$ (cf Aalto *et al.* 1991). We can not, however, exclude significantly larger ΔV which would indicate a continuous, non-cloudy structure — perhaps

even a smooth, rotating disk. A third alternative is a molecular ISM consisting of dense clumps surrounded by diffuse, non-cloudy molecular gas (e.g. Aalto *et al.* 1994,1995; Dahmen *et al.* 1996).

3.2. The overlap region C and NGC 3690

Molecular line ratio variations are also seen within the overlap region C, albeit smaller than those within IC 694. The weakest ^{13}CO and strongest HCN 1–0 emission, relative to ^{12}CO , is found in C1, the location of the brightest H α emission in Arp 299 (Gehrz *et al.* 1983). Continuum emission at 3.4 μm and 10 μm also peaks close to the C1 clump. Thus, C1 appears to be currently the most active starforming region within C. We suggest that the observed molecular line ratio gradients are the result of a temperature and/or density gradient across the overlap region. The $^{12}\text{CO}/^{13}\text{CO}$ 1–0 line ratio in C1 is considerably lower than in the nucleus of IC 694, perhaps because C1 is an extranuclear starburst.

Unlike ^{12}CO , the ^{13}CO emission peak is not connected with the nucleus of NGC 3690 (B1). The radial excitation gradient is similar, therefore, to that of IC 694, with the highest $^{12}\text{CO}/^{13}\text{CO}$ line ratio in the central region. The nucleus of NGC 3690, with intense associated H α emission, is a site of starburst activity (Gehrz *et al.* 1983).

3.3. Molecular abundances

It has been suggested that high $^{12}\text{CO}/^{13}\text{CO}$ intensity ratios in mergers are caused by unusually high isotopic abundance ratios in molecular clouds with optically thick ^{12}CO 1–0 lines. An influx of very low metallicity gas from the outer disk of the galaxies is the proposed cause of such an extreme abundance ratio (e.g. Casoli *et al.* 1992; Henkel & Mauersberger 1993). Since the $^{12}\text{CO}/^{13}\text{CO}$ intensity ratio is normal in the outskirts of

IC 694 and NGC 3690 this scenario is unlikely to be the explanation for Arp 299. Instead, the measured line ratio variations most likely indicate differences in the line excitation and gas properties in different parts of the system.

The observed $^{12}\text{CO}/^{13}\text{CO}$ 1–0 line ratio is, however, a lower limit to the $^{12}\text{CO}/^{13}\text{CO}$ abundance ratio in the emitting region and for $\tau_{10}(^{12}\text{CO}) \lesssim 1$ this implies an abundance ratio not much greater than 60 in the center of IC 694. This value is typical for GMCs in the Galactic disk, but higher than in the inner region of our Galaxy, where the ratio is ≈ 25 (Langer & Penzias 1990). Perhaps the ISM in the nucleus of IC 694 recently arrived from the disk of the galaxy. In this case, the difference in line ratio between A2 and A1 is solely caused by a dramatic change in mean optical depth of the ^{12}CO line. On the other hand, selective photodissociation of ^{13}CO by a starburst and/or an AGN may change the isotopic abundance ratio. A young nuclear starburst may also produce extra ^{12}C and thus temporarily increase the $^{12}\text{C}/^{13}\text{C}$ abundance ratio (e.g., Henkel & Mauersberger 1993).

4. Conclusions

The $^{12}\text{CO}/^{13}\text{CO}$ 1–0 line ratio varies dramatically within Arp 299, from 60 ± 15 at the nucleus of IC 694 to 5–10 in its disk and in the eastern and north interface regions (C3 and D). The ^{13}CO 1–0 brightness, relative to ^{12}CO , is high in quiescent regions of low ^{12}CO surface brightness, and low in starburst regions and galactic nuclei. In contrast, HCN 1–0 is bright in the two galaxy centers and in the active extranuclear star formation region. The $^{12}\text{CO}/\text{HCN}$ 1–0 is 9 ± 1 at the nucleus of IC 694, 14 ± 3 for NGC 3690 and 11 ± 3 for the extranuclear starburst region C1. Unusually high $^{12}\text{CO}/^{13}\text{CO}$ line ratios (> 20) appear to be associated with extremely compact molecular distributions in the nuclei of merging galaxies (cf. Aalto *et al.* 1995).

The large $^{12}\text{CO}/^{13}\text{CO}$ 1–0 intensity ratio at the nucleus of IC 694 can be attributed to low to moderate optical depth ($\tau \lesssim 1$) in the ^{12}CO 1–0 line, possibly combined with abundance effects. A medium consisting of dense ($n = 10^4 - 10^5 \text{ cm}^{-3}$), warm ($T_{\text{k}} > 50 \text{ K}$) gas is consistent with the observations.

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Fig. 1.— (a) ^{12}CO 1–0 moment map (2800–3400 kms^{-1}). Contour levels are 0.9, 1.8, 3.6, 5.4, 7.2, 9, 10.8, 12.6, 14.4, 16.2, and 18 $\text{Jy beam}^{-1} \text{ km s}^{-1}$. Gray scale levels range from 5 to 75 $\text{Jy beam}^{-1} \text{ km s}^{-1}$. The peak flux is 97 $\text{Jy beam}^{-1} \text{ km s}^{-1}$ on the nucleus of IC 694. Crosses mark the 6 cm radio continuum positions (Gehrz *et al.* 1983). (b) The ^{13}CO 1–0 moment map. Contour levels are 0.4, 0.8, 1.2, 1.6, 2.0 $\text{Jy beam}^{-1} \text{ km s}^{-1}$. The peak flux is 2.3 $\text{Jy beam}^{-1} \text{ km s}^{-1}$ on the disk of IC 694. (c) HCN 1–0 moment map. Contour levels are 0.6, 1.2, 1.8, 2.4, 3.0, 3.6, 4.2, 4.8, 5.4 $\text{Jy beam}^{-1} \text{ km s}^{-1}$. The peak flux is 7.1 $\text{Jy beam}^{-1} \text{ km s}^{-1}$ at the nucleus of IC 694.

Fig. 2.— The ^{12}CO 1–0 velocity field. The grayscale range from 2800 (light) to 3300 (dark) kms^{-1} , the contours from 2800 to 3200 kms^{-1} .

Table 1. Arp 299: Source properties

Region	Size ^a	¹² CO 1–0 Intensity			ΔV_{FWHM}	$\frac{^{12}\text{CO 1-0}}{^{13}\text{CO 1-0}}$	$\frac{^{12}\text{CO 1-0}}{\text{HCN 1-0}}$
		Peak	Integrated				(note c)
	[arcsec]	$\left[\begin{array}{c} \text{Jy km s}^{-1} \\ \text{beam}^{-1} \end{array} \right]$	[Jy km s ^{−1}]	[km s ^{−1}]			
IC 694: nucleus (A1)	$\lesssim 1.4$	97	122	350	60 ± 15	9 ± 1	
IC 694: disk (A2)	$17 \times 6^{\text{b}}$	12	120	65	10 ± 3	$> 25 (3\sigma)$	
NGC 3690: nucleus (B1)	$\lesssim 1.5$	29	36	260	...	...
NGC 3690: total	...	...	53	...	13 ± 2	14 ± 3
Overlap east (C3)	3.4×2.2	9	15	60	10 ± 3	$> 20 (3\sigma)$	
Overlap west (C2)	4.3×2.1	20	40	80	...	...
Overlap west (C1)	3.9×2.0	21	47	60	20 ± 4	11 ± 3	
Region D	...	...	4	80	5 ± 3	> 10
Region F	...	...	11	40-80	...	...

^aFWHM from two dimensional Gaussian fits using the AIPS task IMFIT.

^bAn estimate of the size of the SE disk of IC 694 — no Gaussian fit possible.

^cAll ratios are in terms of integrated brightness temperatures. Uncertainties include thermal noise only. The ¹²CO map was smoothed to the resolution of the ¹³CO or HCN map before line ratios were constructed.







