VARIATION OF MOLECULAR LINE RATIOS AND CLOUD PROPERTIES IN THE ARP 299 GALAXY MERGER

S. Aalto
Division of Physics, Mathematics, and Astronomy, Caltech 105-24, Pasadena CA 91125; sab@caltech.edu

Simon J. E. Radford
National Radio Astronomy Observatory, 949 North Cherry Avenue, Tucson, AZ 85721-0665; sradford@nrao.edu

AND

N. Z. Scoville and A. I. Sargent
Division of Physics, Mathematics, and Astronomy, Caltech 105-24, Pasadena CA 91125; nzs@caltech.edu, afs@caltech.edu

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ABSTRACT

High-resolution observations of 12CO (2–1), 13CO (3–2), and HCN (3–2) in the galaxy merger Arp 299 (IC 694 and NGC 3690) show that the line ratios vary dramatically across the system. The 12CO/13CO ratio is unusually large, 60 ± 15, at the IC 694 nucleus, where 12CO emission is very strong, and much smaller, 10 ± 3, in the southern extended disk of that galaxy. Elsewhere, the 12CO/13CO 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 12CO/HCN line ratio also varies across Arp 299, although to a lesser degree. HCN emission is bright toward 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 12CO/13CO 1–0 intensity ratio at the nucleus of IC 694 can primarily be attributed to a low-to-moderate optical depth (τ ≈ 1) in the 12CO 1–0 line. These data support the hypothesis that unusually high 12CO/13CO line ratios (>20) are associated with extremely compact molecular distributions in the nuclei of merging galaxies. Relative to 12CO, 13CO 1–0 is brightest in quiescent regions of low 12CO surface brightness and weakest in starburst regions and the galactic nuclei. A medium consisting of dense (n = 10^4–10^5 cm⁻³) and warm (T_k > 50 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, 10⁷–10¹² M☉ (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 orders of magnitude 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 in understanding the starburst activity and its role in galaxy evolution.

Arp 299 is an IR-luminous (L_IR ≈ 8 × 10¹¹ L☉) merger system of two galaxies, IC 694 and NGC 3690. Strong 12CO 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 (see Gehrz, Sramek, & Weedman 1983; Baan & Haschick 1990). Furthermore, the nucleus of IC 694 is a flat-spectrum radio source and may be an active galactic nucleus (AGN) (Gehrz et al. 1983).

Lower resolution (single-dish) observations reveal an unusually large 12CO/13CO 1–0 line intensity ratio, ≈20 in Arp 299 (Aalto et al. 1991; Casoli, Dupraz, & Combes 1992). These observations left it unclear whether this is due to weak 13CO in the whole system or to a varying 12CO/13CO 1–0 line ratio. Observations at 20″ and 11″ resolution by Casoli et al. (1992) suggest little variation in the 12CO/13CO 1–0 line ratio and none in the 12CO/13CO 2–1 line ratio. In contrast, Aalto et al. (1995) note substantial variations at 28″ resolution in the 12CO/13CO 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 12CO/HCN ratios of 11 in IC 694 and 13 in the interface region.

2. OBSERVATIONS AND RESULTS

Aperture synthesis 12CO, 13CO, and HCN 1–0 mapping of Arp 299 was carried out with the Owens Valley Radio Observatory (OVRO) millimeter array between 1995 March and 1996 February. SIS receivers on the six 10.4 m telescopes provided typical system temperatures (SSB) of 600 K, 450 K, and 350 K for 12CO, 13CO, and HCN. Quasars 1150+497 and 0917+449 were used for phase calibration, and Uranus and Neptune for absolute flux calibration. The synthesized beams are 2′′5 × 2′′2 for 12CO (uniform weighting), 4′′3 × 3′′6 for 13CO (natural weighting), and 5′′6 × 5′′3 for HCN (natural weighting).
weighting). At 2.6 mm wavelength with 2\arcmin.3 resolution, a brightness temperature of 1 K corresponds to 57 mJy beam\(^{-1}\). The digital correlator, centered at \(V_{\text{LSR}} = 3100\) 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\,H\(_2\) mJy was detected in the center of IC 694. Continuum emission was also detected in NGC 3690 (5 \pm 2 mJy) and the overlap region (9 \pm 2 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-telescope array are recovered in our new \(^{12}\)CO map (Fig. 1a), but our increased \(uv\) coverage enables improved deconvolution. Lower surface brightness emission (A2), possibly a molecular disk or bar, extends 10\arcsec--15\arcsec 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 \(\approx 3280\) 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\farcs5). 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\farcs5, although the discrepancy between C2 and the eastern radio continuum peak is somewhat larger, \(\Delta\alpha = 0\farcs8\). 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 (Fig. 2 [Pl. L13]) 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 22′2 synthesized 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 \( D = 42 \) Mpc). This implies a lower limit of 18 K to the \(^{12}\text{CO}\) 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).

**TABLE 1**

| REGION          | SIZE \(^a\) (arcsec) | PEAK \(^b\) (Jy km s \(^{-1}\) beam \(^{-1}\)) | INTEGRATED \(^b\) (Jy km s \(^{-1}\)) | \( \Delta V_{FWHM} \) (km s \(^{-1}\)) | \( ^{12}\text{CO}1–0\) \(^b\) | \( ^{13}\text{CO}1–0\) \(^b\) |
|-----------------|----------------------|------------------------|------------------|--------------------------|----------------|----------------|
| IC 694: nucleus (A1) | \( \leq 1.4 \) | 97 | 122 | 350 | 60 ± 15 | 9 ± 1 |
| IC 694: disk (A2) | 17 × \( 6^{c} \) | 12 | 120 | 65 | 10 ± 3 | >25 (3 \( \sigma \)) |
| NGC 3690: nucleus (B1) | \( \leq 1.5 \) | 29 | 36 | 260 | \ldots | \ldots |
| NGC 3690: total | \ldots | \ldots | \ldots | \ldots | \ldots | \ldots |
| Overlap east (C3) | 3.4 × 2.2 | 9 | 15 | 60 | 10 ± 3 | 14 ± 3 |
| Overlap west (C2) | 4.3 × 2.1 | 20 | 40 | 80 | \ldots | \ldots |
| Overlap west (C1) | 3.9 × 2.0 | 21 | 47 | 60 | 20 ± 4 | 11 ± 3 |
| Region D | \ldots | \ldots | \ldots | \ldots | \ldots | \ldots |
| Region F | \ldots | 11 | 40–80 | \ldots | \ldots | \ldots |

\(^a\) FWHM from two-dimensional Gaussian fits using the AIPS task IMFIT.

\(^b\) All ratios are in terms of integrated brightness temperatures. Uncertainties include thermal noise only. The \(^{12}\text{CO}\) map was smoothed to the resolution of the \(^{13}\text{CO}\) or HCN map before line ratios were constructed.

\(^c\) An estimate of the size of the southeast disk of IC 694—no Gaussian fit possible.

## 3. THE MOLECULAR LINE RATIOS

As a system, Arp 299 is not deficient in \(^{13}\text{CO}\). 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 \(^{12}\text{CO}\), \(^{13}\text{CO}1–0\) is brightest in quiescent regions of low \(^{12}\text{CO}\) surface brightness, and weak in starburst regions and galactic nuclei. In contrast, HCN 1–0, like \(^{13}\text{CO}\), 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 \(^{12}\text{CO}1–0\) 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 \(^{12}\text{CO}\) 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 \(^{13}\text{CO}\) emission (HCN/\(^{13}\text{CO} = 7 ± 2\)) implies a population of unusually dense and warm clouds. The HCN 1–0 strength implies densities \( n \approx 10^{6} \text{ cm}^{-3} \) if the HCN excitation is dominated by collisions with \(^{2}\text{H}_2\). It is also likely that the density is \( \approx 10^{7} \), so that most of the HCN population will remain in the lower levels and \( \tau_{01} > 1 \). At these densities, the \(^{12}\text{CO}\) and \(^{13}\text{CO}1–0\) transitions are thermalized. 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 \(^{13}\text{CO}2–1/1–0\) line ratio should be greater than 1. Comparing the single-dish \(^{13}\text{CO}2–1\) flux (Aalto et al. 1995) with our \(^{13}\text{CO}1–0\) flux from the nucleus of IC 694, we estimate that \(^{13}\text{CO}2–1/1–0 \approx 2\), implying that the gas temperature is high, greater than 50 K. Although the single-dish beam was large, 28′, the bulk (\( \approx 65\% \)) of the \(^{13}\text{CO}2–1\) emission within the beam originates in the nucleus of IC 694 (A1).

Since the lower transitions of \(^{13}\text{CO}\) and \(^{12}\text{CO}\) appear ther-
Galaxy. At this gas density, HCN is not thermalized, so unlike cores or clumps within giant molecular clouds in the forefront we assume that $\tau_{\rm d}(\text{HCN}) \approx 3.9 \times 10^{-5} N(\text{HCN})(1 - e^{-3.53/\sigma})/T_b \Delta V$. For a temperature $T_b = 100$ K, line width $\Delta V = 5$ km s$^{-1}$, and $\tau_{\rm d} = 1$, the HCN column density $N(\text{HCN}) = 2 \times 10^{18}$ cm$^{-2}$ (per cloud), and the resulting brightness temperature $T_b(\text{HCN}) \approx 60$ K. For a density of $n = 10^5$ cm$^{-3}$ and a $\text{HCN}$ abundance, $[\text{HCN}]/[\text{H}_2] = 5 \times 10^{-5}$, the cloud radius $r = N(\text{HCN})/2\pi(\text{HCN})n(\text{H}_2) = 0.7$ pc—not unlike cores or clumps within giant molecular clouds in the Galaxy. At this gas density, HCN is not thermalized, so $\tau_{\rm d}(\text{HCN}) \approx 1$. The depth of the $1-0$ transition can be expressed as $\tau_{\rm d}(\text{HCN}) \approx 3.9 \times 10^{-5} N(\text{HCN})(1 - e^{-3.53/\sigma})/T_b \Delta V$. For a temperature $T_b = 100$ K, line width $\Delta V = 5$ km s$^{-1}$, and $\tau_{\rm d} = 1$, the HCN column density $N(\text{HCN}) = 2 \times 10^{18}$ cm$^{-2}$ (per cloud), and the resulting brightness temperature $T_b(\text{HCN}) \approx 60$ K. For a density of $n = 10^5$ cm$^{-3}$ and a $\text{HCN}$ abundance, $[\text{HCN}]/[\text{H}_2] = 5 \times 10^{-5}$, the cloud radius $r = N(\text{HCN})/2\pi(\text{HCN})n(\text{H}_2) = 0.7$ pc—not unlike cores or clumps within giant molecular clouds in the Galaxy. At this gas density, HCN is not thermalized, so $\tau_{\rm d}(\text{HCN}) \approx 1$.

Above, we infer a clumpy molecular medium because we chose $\Delta V = 5$ km s$^{-1}$, yielding small clouds with $r < 1$ pc (see Aalto et al. 1991). We cannot, however, exclude significantly larger $\Delta V$ that would indicate a continuous, nonclumpy structure—perhaps even a smooth, rotating disk. A third alternative is a molecular interstellar medium (ISM) consisting of dense clumps surrounded by diffuse, nonclouidy molecular gas (e.g., Aalto et al. 1994, 1995; Dahmen et al. 1996).

3.2. The Overlay Region C and NGC 3690

Molecular line ratio variations are also seen within the overlay region C, albeit smaller than those within IC 694. The weakest $^{13}$CO and strongest HCN 1–0 emission, relative to $^{12}$CO, are found in C1, the location of the brightest He$^+$ emission in Arp 299 (Gehrz et al. 1983). Continuum emission at 3.4 $\mu$m and 10 $\mu$m also peaks close to the C1 clump. Thus, C1 appears to be currently the most active star-forming region within C. We suggest that the observed molecular line ratio gradients are the result of a temperature and/or density gradient across the overlay region. The $^{12}$CO/$^{13}$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 $^{13}$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 $^{12}$CO/$^{13}$CO line ratio in the central region. The nucleus of NGC 3690, with intense associated H$\alpha$ emission, is a site of starburst activity (Gehrz et al. 1983).

3.3. Molecular Abundances

It has been suggested that high $^{12}$CO/$^{13}$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 $^{12}$CO/$^{13}$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 $^{12}$CO/$^{13}$CO 1–0 line ratio is, however, a lower limit to the $^{12}$CO/$^{13}$CO abundance ratio in the emitting region, and for $\tau_{\rm d}(^{12}$CO) $\approx 1$ 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 $\approx 25$ (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 $^{13}$C and thus temporarily increase the $^{13}$C/$^{12}$C abundance ratio (e.g., Henkel & Mauersberger 1993).

4. CONCLUSIONS

The $^{12}$CO/$^{13}$CO 1–0 line ratio varies dramatically within Arp 299, from 60 $\pm$ 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 $^{12}$CO/HCN 1–0 is $9 \pm 1$ at the nucleus of IC 694, $14 \pm 3$ for NGC 3690, and $11 \pm 3$ for the extranuclear starburst region C1. Unusually high $^{12}$CO/$^{13}$CO line ratios ($>20$) appear to be associated with extremely compact molecular distributions in the nuclei of merging galaxies (see Aalto et al. 1995).

The large $^{12}$CO/$^{13}$CO 1–0 intensity ratio at the nucleus of IC 694 can be attributed to low-to-moderate optical depth ($\tau \approx 1$) in the $^{12}$CO 1–0 line, possibly combined with abundance effects. A medium consisting of dense ($n = 10^5-10^6$ cm$^{-3}$), warm ($T_k > 50$ K) gas is consistent with the observations.

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Fig. 2.—The $^{12}$CO 1–0 velocity field. The gray-scale ranges from 2800 (light) to 3300 (dark) km s$^{-1}$, the contours from 2800 to 3200 km s$^{-1}$.

Alto et al. (see 475, L108)