INFRARED LINE EMISSION IN THE INTERACTING REGION OF ARP 244 (THE ANTENNAE): COLLIDING MOLECULAR CLOUD COMPLEXES?

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ABSTRACT

We report velocity-resolved spectroscopy of infrared hydrogen recombination lines in the interacting region of the Antennae galaxies (NGC 4038/4039). It generally has been assumed that the active star formation found there is due to the interaction of the disks of the two galaxies and indeed two molecular cloud complexes, separated in velocity by \( \sim 100 \text{ km s}^{-1} \), have been observed in the southern part of this region. Our measurements imply that the two cloud complexes are moving away from each other. This result poses interesting questions about the physical mechanisms leading to starbursts in Arp 244 and other interacting galaxies.

Subject headings: galaxies: interactions — galaxies: kinematics and dynamics — galaxies: starburst — infrared: galaxies

1. INTRODUCTION

The Antennae (NGC 4038/4039, Arp 244, VV 245) are a nearby (\( \sim 22 \text{ Mpc} \)) infrared-luminous pair of interacting galaxies. Using \( N \)-body numerical simulations, Toomre & Toomre (1972) succeeded in generating the long tidal tails seen in optical/H \( \alpha \) images of the galaxies (van der Hulst 1979). The strongest emission in both the radio continuum (Hummel & van der Hulst 1986) and the CO (1–0) line (Sanders & Mirabel 1985; Stanford et al. 1990; Aalto et al. 1995; S.-W. Lee, K. Y. Lo, R. A. Gruendl, & Y. Gao 2001, in preparation, hereafter L01) occurs in the interaction (overlap) region to the west and between the two nuclei, especially in its southern dense clouds. The Hubble Space Telescope (HST) H\( \alpha \) image of the Antennae reveals thousands of giant H \( \alpha \) regions in the interaction region. X-ray observations (Fabbiano & Trinchieri 1983) show harder and softer components corresponding to supernova remnants/X-ray binaries and thermal emission from gas possibly heated by the interaction, respectively. These observations all point to there being copious numbers of active star formation sites in the interacting region.

Mid-infrared (12–17 \( \mu \text{m} \)) observations (Mirabel et al. 1998) of the Antennae by the Infrared Space Observatory (ISO) confirm that the starburst is taking place largely in portions of the interaction region that are highly optically obscured. The ratio of [Ne \( \text{ii} \)] and [Ne \( \text{ii} \)] mid-infrared lines indicates that stars as massive as 60 \( M_{\odot} \) are present there (Vigroux et al. 1996; Mirabel et al. 1998). The peak of [C \( \text{ii} \)] 158 \( \mu\text{m} \) fine-structure line also lies in the interaction region, but overall the ratio of [C \( \text{ii} \)] to CO is a factor of 2.6 lower than usual starburst galaxies, suggesting that global star formation is not taking place in the Antennae (Nikola et al. 1998).

Using the BIMA array with a 778 \( \times \) 666 beam, L01 have found that there are two kinematically distinct molecular cloud complexes separated by \( \sim 100 \text{ km s}^{-1} \) in the southern part of the overlap region (see Fig. 1), corresponding roughly to super giant molecular complexes 4 and 5 found by Wilson et al. (2000). It seems likely that each of these is associated with one of the interacting galaxies. Because their relative positions along the line of sight are unknown, it is unclear whether the complexes are approaching or moving away from each other. If the redshifted cloud complex is in front, it may collide with a blueshifted cloud, and subsequently a starburst, perhaps greater than that currently being observed, may occur. If the blueshifted clouds are in front, then the complexes are moving away from each other, and the bulk of their interaction, if any, already has taken place in this region.

Comparison of velocity profiles of properly chosen emission lines, well separated in wavelength but from similarly excited species, could clarify the situation since velocity components associated with the two complexes should undergo different amounts of extinction. UV and optical lines associated with star formation in these clouds are expected to be essentially totally obscured by dust. With this in mind, we have observed the hydrogen infrared recombination lines Pa\( \beta \) (5–3, 1.282 \( \mu\text{m} \)), Br\( \gamma \) (7–4, 2.166 \( \mu\text{m} \)), and Br\( \alpha \) (5–4, 4.052 \( \mu\text{m} \)) from part of the overlap region.

2. OBSERVATIONS AND DATA REDUCTION

The observations were made during UT 2000 February 28–March 1 at the United Kingdom Infrared Telescope (UKIRT) on Mauna Kea, using the facility cooled grating spectrometer CGS4 (Mountain et al. 1990) equipped with a 256 \( \times \) 256 InSb array. All three nights were clear with stable but not exceptional seeing. We selected the 31 line mm\(^{-1}\) echelle, 300 mm focal length camera optics, and 2 pixel–wide (0.78) slit, which give CGS4 a velocity range of \( \sim 2000 \text{ km s}^{-1} \) at any wavelength in the 1–5 \( \mu\text{m} \) region at a resolution of \( \sim 16 \text{ km s}^{-1} \) (2 pixels). The \( \sim 80^\circ\)-long slit was oriented north-south for all observations. Sky measurements were obtained with the telescope nodded 600" to the west.

On the first night, we centered the slit on the southern CO peak at J2000 R.A. = 12°01'55", decl. = \( -18^\circ53'01.5" \), detecting weak line emission at Pa\( \beta \) and Br\( \gamma \) but no emission at Br\( \alpha \). On the following two nights, we positioned the slit 3" west of the CO peak, which corresponds to the location of strongest mid-infrared emission as measured by ISO. There we detected all three recombination lines at four spatially distinct locations along the slit (see Fig. 1), which we call apertures I–IV (in the order from north to south). Details of the locations are provided in Table 1.

The data were wavelength-calibrated to an accuracy of...
Fig. 1.—CO (1–0) zero-moment low-resolution (7.8 × 6.6) contour map (L01) overlaid on the HST three-color (Hα, V-band, and B-band) image. The long vertical crosses indicate the locations along the slit where IR recombination lines were detected; from top to bottom, these are apertures I–IV. The solid contours represent the red component of the CO emission in the interaction region and the CO emissions in each nuclei (contour levels are 6 Jy beam⁻¹ km s⁻¹ times 4, 7, 10, 12, 14, 17, 20, and 25). The dashed contours are the blue component of the CO emission in the interaction zone (levels are 5 Jy beam⁻¹ km s⁻¹ times 5, 9, 13, 17, and 21).

5 km s⁻¹ using spectra of arc lamps and night-sky emission lines and flux-calibrated using the A5 V star HR 4405 (V = 4.10), which is assumed to have the visible–infrared colors given in Tokunaga (1999) for such stars. From the point-spread functions along the slit, we estimate that at the wavelength of each recombination line, 0.60 ± 0.05 of the stellar flux entered the slit on each night. Spectra were summed over ~10 adjacent rows at each of the four spatially distinct line-emitting regions. Data from the final two nights were combined to yield the spectra shown in Figure 2. The figure also includes CO spectra obtained by L01 at those locations. The basic results are summarized in Table 2.

3. RESULTS

3.1. Spatial and Velocity Distributions

Figure 2 shows broad recombination line emission, covering 100–200 km s⁻¹, at each of the four locations along the slit. A faint continuum is detected in some spectra. Apertures I and II are located near the local maxima of CO emission in the northern part of the interacting region, where Wilson et al. (2000) and L01 have found largely redshifted CO emission. Apertures III and IV fall into the southern part of the interacting region, where L01 found overlapping red and blue components separated by ~100 km s⁻¹.

In the two northern apertures, the velocities and profiles of the infrared lines generally match those of the CO emission. At aperture I, both the atomic and molecular line profiles show peaks near $V_{LSR} = 1600$ km s⁻¹, close to the velocities of the nuclei (the NASA/IPAC Extragalactic Database gives radial velocities near 1640 km s⁻¹ for both NGC 4038 and NGC 4039), and a blue asymmetry in the wings, and at aperture II, both show a more symmetric line profile peaked near the same velocity. In the south, however, there are distinct differences between the millimeter and infrared velocity profiles. Most of the infrared line emission at aperture III occurs near $V_{LSR} = 1400$ km s⁻¹, ~100 km s⁻¹ to the blue of the velocity of CO peak emission and in fact further blueshifted than almost all of the CO. No infrared line emission is present near 1600 km s⁻¹, the peak of the CO redshifted component. At aperture IV, the velocities of peak emission are ~1500 km s⁻¹ for both the infrared and millimeter lines, but little or no redshifted emission, which is seen in CO near $V_{LSR} = 1600$ km s⁻¹, is detected in any of the infrared lines.

Fig. 2.—Spectra at apertures I–IV. The unit of flux density for the infrared lines is $10^{-15}$ W m⁻² μm⁻¹.
At none of the locations are there more than marginally significant differences between the profiles of the three infrared lines. However, the signal-to-noise ratios are not high, especially for Brα, so modest differences in profiles cannot be ruled out. In contrast, the differences between the CO and hydrogen profiles are large, especially at the southern positions.

### 3.2. Extinction

The CO measurements of L01 and the infrared line measurements reported here each provide a means for estimating extinction. Using the mean CO-to-H$_2$ conversion factor determined for our Galaxy (e.g., Rand, Lord, & Higdon 1999; Bryant & Scoville 1999),

$$X = \frac{N(H_2)}{I_{CO}} = 2.5 \times 10^{20} \text{H}_2 \text{cm}^{-2} (\text{K km s}^{-1})^{-1}$$

$$= 6.2 \times 10^{11} \text{H}_2 \text{cm}^{-2} (\text{Jy km s}^{-1})^{-1},$$

and the gas-to-dust ratio of Bohlin, Savage, & Drake (1978),

$$N(H_2) = 0.94 \times 10^{23} A_v \text{cm}^{-2} \text{mag},$$

determine that the visual extinctions through the molecular gas at apertures I and II are 18 and 15 mag, respectively. Those at apertures III and IV are much larger, $A_v \approx 45$ mag and $A_v \approx 46$ mag, respectively. All of these estimates incorporate both interferometric and single-dish observations. It is known that in some starburst galaxies, the conversion factor is up to 3 times smaller than in our Galaxy (Smith et al. 1991; Downes & Solomon 1998), and therefore it is possible that the extinctions are proportionately less in the Antennae overlap region.

To derive the extinctions to the infrared line-emitting regions, we assumed typical H II region conditions ($T_e = 10^4$ K, $n_e = 10^4$ cm$^{-3}$), for which the intrinsic ratios are 0.162, 0.0275, and 0.0777 for Paβ/Hβ, Brγ/Hβ, and Brα/Hβ, respectively (Hummer & Storey 1987). We employed the formula obtained by Rieke & Lebofsky (1985) for 0.9–3.4 μm, along with an interpolation of their $L$- and $M$-band extinctions, obtaining factors of 0.270 at Paβ, 0.115 at Brγ, and 0.042 at Brα relative to visual extinction. We used the total integrated line fluxes as described in Table 2; the overall general agreement of the three infrared line profiles at each aperture suggests that at each location, the detected lines are attenuated by the same clouds.

The results are tabulated in Table 3. Significantly different values are obtained for different pairs of lines at two of the four locations. At all four locations, the smallest value corresponds to the shortest wavelength pair (Paβ/Brγ), and the largest value corresponds to the longest wavelength pair (Brγ/Brα). This indicates that, rather than a single source of line emission and an obscuring screen, there are distributions of line emission and attenuating clouds along the lines of sight at each location (Puxley 1991).

### 4. Locations of the Clouds

The extinctions derived from the hydrogen recombination lines (Table 3) are low compared with those derived from the CO measurements (Table 1). This is the case even if the extinctions through the molecular clouds are a factor of 3 less (as discussed in § 3.2), except for the largest value derived for aperture I. The results indicate that most of the observed recombination line flux in each of the four apertures is emitted near the front surface of the associated cloud complex, and, moreover, for apertures III and IV, that complex must be the only one that is absorbing and hence the one that is closer to us. Although the velocities and profiles of the infrared lines at apertures III and IV do not closely match those of either molecular cloud, it is much more likely that these blueshifted lines are associated with the blueshifted molecular cloud than with the redshifted one. Thus, we conclude that the blueshifted molecular cloud is in the foreground.

A second approach makes use of the lack of redshifted line emission in the region where the clouds overlap, although redshifted emission is present in the northern region where the blueshifted cloud is absent. The nondetection at aperture III implies either that no redshifted recombination line emission occurs there or that high extinction makes the infrared lines unobservable. For the latter case, if we assume the same ratios of infrared line emission to CO line emission in aperture III as in aperture I or II, we obtain rough lower limits for $A_v$ to the redshifted cloud. These may be compared with the values of $A_v$ obtained from the CO line strength (Table 1) to infer the geometry. We obtain lower limits to $A_v$ at redshifted velocities of $\approx 8$, $\approx 20$, and $\approx 27$ mag for Paβ, Brγ, and Brα, respectively. The most restrictive of these, the Brγ and Brα limits, rule out extinction by the redshifted cloud alone, even if that emission originates entirely behind it. We conclude that both clouds would be required to produce the extinction, and therefore, at aperture III, we again infer that the blueshifted cloud complex is in front of the redshifted complex. The above argument could be incorrect if the recombination line emission from the red component in aperture III is intrinsically weak. At aperture IV, it is more difficult than at aperture III to separate clearly the two cloud complexes based on the CO velocity profile, so this...
test is more problematic than for aperture III, although it tends to suggest the same conclusion.

The significant blueshift of the infrared lines at aperture III relative to the blueshifted molecular component is apparent even at the highest resolution (~2") CO measurements of L01. This nearly complete lack of overlap in velocities is somewhat surprising. We propose two possible explanations: (1) The ionized gas lies close to the front surface of the blueshifted molecular cloud complex and is largely accelerated outward and toward the observer, and (2) the stars with which the ionized gas is associated have a different velocity distribution than the molecular cloud.

Several possibilities exist to test the correctness of our conclusions about the relative positions of the molecular cloud complexes along the line of sight. Measurements of the CO lines at higher angular resolution would better match the spatial resolution of the infrared measurements. Alternatively, spectral mapping of the infrared lines would allow a better comparison with the present CO observations. Searches for redshifted radio recombination line emission could determine whether any ionized gas, undetected at infrared wavelengths, is associated with the molecular cloud.

5. SUMMARY AND CONCLUDING DISCUSSION

We have obtained velocity-resolved spectra of three infrared hydrogen recombination lines, covering a wide range of wavelengths, in the interaction region of the Antennae galaxies, where millimeter CO observations have revealed two distinct clouds of gas with widely different radial velocities. Using an empirical extinction formula, standard recombination line ratios, and the standard gas-to-dust conversion factor, we infer that the two molecular clouds currently are moving away from each other. This is contrary to the conventional expectation of cloud collisions leading to starburst activities (e.g., Wilson et al. 2000).

The age of the starburst in the interacting region has been estimated to be 3–4 Myr (Hummel & van der Hulst 1986; Neff & Ulvestad 2000). If this starburst were due to cloud collisions, then at present the clouds can only be separated (along the line of sight) by 100 km s\(^{-1}\) times a few megayears or ~300 pc. The cloud complexes are about 1 kpc in extent in the plane of the sky. If they are roughly spherical, they would still be physically overlapped in the radial direction. Yet we observe two well-defined components moving apart at 100 km s\(^{-1}\). How this physical arrangement of the molecular clouds might have occurred is not clear. There is no easy way to determine the radial separation, if any, of the two molecular cloud complexes, although, in principle, one could model the interaction of the gas in Arp 244 in sufficient detail to see if this physical situation is plausible. The morphology of the molecular cloud complexes (Fig. 1) does not suggest physical proximity.

If the starbursts currently observed are not due to direct cloud collisions, the physical mechanisms initiating them require further investigation. Current observational evidence of molecular gas in starburst regions points to two characteristic parameters: high column density (Downes & Solomon 1998; Bryant & Scoville 1999) and high density (Solomon, Downes, & Radford 1992; Downes & Solomon 1998). If high column density and high density (both of which are naturally expected in the process of gravitational collapse) are causal factors for starbursts, then the issue reduces to identifying the mechanisms during galaxy interaction that lead to the concentration of a large amount of molecular gas in regions such as the interacting region in Arp 244.

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