[C II] EMISSION FROM NGC 4038/9 (THE \"ANTENNAE\")

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ABSTRACT

We present observations of NGC 4038/9 in the [C II] 158 μm fine-structure line taken with the MPE/UCB Far-infrared Imaging Fabry-Perot Interferometer (FIFI) on the Kuiper Airborne Observatory (KAO). A fully sampled map of the galaxy pair (without the tidal tails) at 55° resolution has been obtained. The [C II] emission line is detected from the entire galaxy pair and peaks at the interaction zone. The total [C II] luminosity of the Antennae is \(L_{\text{[C II]}} = 3.7 \times 10^8 L_\odot\), which is about 1% of the far-infrared luminosity observed with IRAS. The main part of the [C II] emission is probably produced by photodissociation regions (PDRs), and a minor fraction may be emitted from H II regions. A small part of the [C II] emission comes from a standard cold neutral medium (CNM); however, for high temperatures (\(T \sim 100\) K) and high densities (\(n_H \sim 200\) cm\(^{-3}\)) of the CNM, up to about one third of the observed [C II] emission may originate from CNM. From PDR models, we derive densities on the order of \(\sim 10^5\) cm\(^{-3}\) and far-UV (FUV) intensities of 46\(\times\)\(10^{-2}\) erg cm\(^{-2}\) s\(^{-1}\) for the PDRs in the interaction zone, NGC 4038, and NGC 4039, respectively. However, PDRs with densities on the order of \(\sim 10^2\) cm\(^{-3}\) and FUV intensities on the order of \(\sim 100\) erg cm\(^{-2}\) s\(^{-1}\) could also explain the observed [C II] emission. The minimum masses in the [C II]-emitting regions in the interaction zone and the nuclei is a few \(\times 10^7\) \(M_\odot\).

A comparison with single-dish CO observations of the Antennae shows a [C II] to CO intensity ratio at the interaction zone that is a factor of 2.6 lower than usually observed in starburst galaxies, but still a factor of about 1.3 to 1.4 higher than at the nuclei of NGC 4038/9. Therefore, no global starburst is taking place in the Antennae. [C II] emission arising partly from confined starburst regions and partly from surrounding quiescent clouds could explain the observed [C II] radiation at the interaction zone and the nuclei. Accordingly, there are small confined regions with high star formation activity in the interaction zone and with a lower star formation activity in the nuclei. This supports the high density and high FUV intensity of the PDRs in the interaction zone and the nuclei.

Subject headings: galaxies: interactions — galaxies: individual (NGC 4038/9) — infrared: galaxies

1. INTRODUCTION

The galaxy pair NGC 4038/9 (Arp 244) is an interacting system in an early stage of merging at a distance of about 21 Mpc from our own galaxy. On long-exposure images in the optical (e.g., Arp 1966), the interaction is clearly visible because of the tails (\"Antennae\") emerging from two uniformly luminous, partly overlapping ovals and because of the dwarf galaxy that appears to have formed at the tip of the southern tail through the interaction (Zwicky 1956; Schweizer 1978; Mirabel, Dottori, & Lutz 1992). The tails contain about 70% of the total amount of H I in the system (van der Hulst 1979). Short-exposure images (Laustsen, Madsen, & West 1987) reveal hints of the interaction on somewhat smaller scales; the distorted arrangement of Hz knots and the velocity distribution of the individual knots lead Rubin, Ford, & D’Odorico (1970) to conclude there is an interaction of two rotating galaxies. Computer simulations carried out in the classical paper of Toomre & Toomre (1972) and later by Barnes (1988) can account for the present morphological appearance of the system quite well by assuming an interaction of two rotating spiral galaxies.

Spectra of the nuclei of both galaxies taken in the optical range do not look like pure starburst spectra, but consist of a composition of early-type stars and late giants (Keel et al. 1985). The detection of bright near-infrared peaks at the nuclei lead Bushouse & Werner (1990) to the same result. Their images of the Antennae in the J and R bands and in Hz show the same pattern of bright knots in the surroundings of NGC 4038 and in the bridge connecting the two galaxies. The Antennae system as a whole shows a relatively low star-forming efficiency according to the ratio \(L_{\text{IR}}/M(\text{H}_2) \approx 8.55\) measured by Young et al. (1986); this is only a factor of 3 higher than in the Milky Way. The ratio determined by Sanders & Mirabel (1985) is almost twice as high. However, they observed a smaller region in CO and therefore probably underestimated the molecular mass. A comparison of the Antennae with the sample of interacting and isolated galaxies of Young et al. (1986) shows NGC 4038/9 to have characteristics more like isolated galaxies.

Measurements of NGC 4038/9 in the radio continuum at 1.5 and 4.9 GHz (Hummel & van der Hulst 1986) reveal a number of discrete knots that coincide in general with Hz...
knots, and an underlying diffuse component. This diffuse component has a steep spectral index on average, which indicates nonthermal emission, and the peak of the diffuse radio emission is at the dust patch near the overlapping region. The discrete radio knots account for roughly 35% of the total radio emission and have a spectral index of $\alpha \approx -0.5$ on average, probably as the result of a thermal contribution (Hummel & van der Hulst 1986).

Interferometric observations of the Antennae in CO (1 → 0) by Stanford et al. (1990) show three main concentrations of CO emission. Two are associated with the nuclei, and the third with the interaction zone. The overlap region is the strongest CO source and contains $\approx 10^9 M_\odot$ of gas, roughly as much H$_2$ as both nuclei together. Based on 10 $\mu$m and H$_2$ data, the authors have calculated a star formation rate of $5 M_\odot$ yr$^{-1}$; consequently, the lifetime of the molecular gas is $2 \times 10^8$ yr. Single-dish observations in CO were made at the interaction zone and both nuclei of the Antennae by Aalto et al. (1995). The ratio of the emission lines of $^{12}$CO and $^{13}$CO measured in the nuclei and the overlapping region of the Antennae is similar to that found in the central regions of “normal” starburst galaxies (Aalto et al. 1995).

An excellent tracer of star formation activity in galaxies is the strong [C II] 158 $\mu$m $^2P_{3/2} \rightarrow ^2P_{1/2}$ fine-structure line that arises mainly from photodissociation regions (PDRs) created by far-ultraviolet photons from hot young stars impinging on nearby dense interstellar clouds (Crawford et al. 1985; Stacey et al. 1991). In combination with CO and FIR observations, the [C II] emission can be used with PDR models (Tielens & Hollenbach 1985; Wolfire, Hollenbach, & Tielens 1989; Wolfire, Tielens, & Hollenbach 1990) to derive densities and far-UV intensities and estimate the star formation activity. Extragalactic surveys of [C II] emission (Crawford et al. 1985; Stacey et al. 1991) concentrated mainly on nuclei, while more recent observations have imaged individual galaxies in order to study the distribution of [C II] emission on large scales. [C II] images of M83 (Geis et al. 1998) and NGC 6946 (Madden et al. 1993) demonstrate that the emission is extended at least over the full optical extent, and that it often follows the distribution of the FIR and CO within the disks of the galaxies. In the case of NGC 6946, [C II] emission beyond the optical extent of the galaxy has been found. This [C II] emission has been attributed to diffuse gas and not to PDRs. Therefore, we also estimate the possible contribution of [C II] emission from neutral atomic gas and from ionized gas in NGC 4038/9. Because of its relative proximity, NGC 4038/9 is a unique source for carrying out spatially resolved measurements of the [C II] line in an interacting system. We present the results of our imaging spectroscopy study of the [C II] line in NGC 4038/9 and compare them with observations obtained with the Infrared Space Observatory (ISO).

2. OBSERVATIONS

Observations of the Antennae in the [C II] $^2P_{3/2} \rightarrow ^2P_{1/2}$ fine-structure line at 157.7409 $\mu$m have been carried out during four individual flights in 1992 with the Kuiper Airborne Observatory (KAO) from Christchurch, New Zealand, using the MPE/UCB Far-infrared Imaging Fabry-Perot Interferometer (FIFI; Poglitsh et al. 1991; Stacey et al. 1992). At 158 $\mu$m, the FWHM of the beam is about 55". The detector array consists of 5 × 5 pixels of size 40" × 40" per pixel on the sky. We observed three array positions to cover an area of 300" × 300", including both galaxies and the interaction zone, and to fully sample an area of 150" × 150" around the interaction zone. Because of the large velocity dispersion in one array setting, as determined from the emission of the H$_2$ knots (Rubin et al. 1970) and from the CO emission (Stanford et al. 1990), we chose a spectral resolution of 144 km s$^{-1}$ (FWHM) and a scan width of 380 km s$^{-1}$. The scan center was set at 1600 km s$^{-1}$. The wavelength calibration was implemented by means of the H$_2$S absorption line at 157.7726 $\mu$m. Flat-fielding of the detector was carried out with two internal blackbodies. The secondary mirror of the telescope was chopped approximately 4" in a roughly east-west direction, and the telescope was nodded to compensate for the beam offset. For absolute intensity calibration, we observed Jupiter at 158 $\mu$m and assumed a temperature of 128 K at this wavelength (Hildebrand et al. 1985), an equatorial diameter of 43"22, and a pole diameter of 40"42 (Astronomical Almanac 1992) for Jupiter. The accuracy of the intensity calibration is estimated to be about 30%, and the absolute pointing positions are uncertain by about 15".

3. DATA REDUCTION

The Fabry-Perot interferometers in FIFI are adjusted to the appropriate velocity range and spectral resolution for every object. In addition, the Fabry-Perot interferometers are put into a “park” position when the instrument is not in use. Therefore, the Fabry-Perot interferometers are newly adjusted for every observing flight and for every object, so there may be slight shifts (of approximately a few km s$^{-1}$) in the velocity center of the spectral scans between individual observations.

To combine the different pointings of the observation of the Antennae obtained in different observing flights, we used the velocity range contained in all observations (1420–1740 km s$^{-1}$). We constructed a program using the method of maximum entropy to combine the different array positions, to account for the statistical errors in the data, and to regrid the data points on a regular grid. This program mainly follows the procedure of Gull & Daniel (1978), as described in Skillings & Bryan (1984). It determines the maximum entropy of an image that consists of model data points on a preset regular grid, on the condition that the model data, after convolving with the beam, fit the observed data according to a $\chi^2$ fit. For large N, the program stops if $\chi^2$ is approximately equal to $N + 3.29(N)^{1/2}$, where N is the number of observed data points (Skilling & Bryan 1984). This criterion corresponds to a 99% confidence level for the $\chi^2$ fit. The observed data points were deconvolved and regrided with this program onto a 10" regular grid and smoothed with a 55" Gaussian beam.

Taking the peculiar velocity structure of the Antennae (as seen, for example, in Hz; Amram et al. 1992) into account and using spectral separation, we can distinguish different components of the system that are not spatially resolved. We therefore subdivided the total velocity range into two velocity ranges ($v = 1420–1554$ km s$^{-1}$ and $v = 1550–1740$ km s$^{-1}$), in order to distinguish between the interaction zone (at roughly $v = 1450–1590$ km s$^{-1}$) and the nuclei (at $v = 1600$ km s$^{-1}$ for NGC 4039, the southern galaxy, and $v = 1630$ km s$^{-1}$ for NGC 4038, the northern galaxy; Amram et al. 1992; Rubin et al. 1970; Stanford et al. 1990). The cut in the velocity range is somewhat arbitrary, since on the one hand the velocity gradient between the inter-
action zone and NGC 4039 is large, and on the other hand no clear spatial transition in the velocity occurs between NGC 4038 and the interaction zone.

To obtain the \([\text{C} \\text{II}]\) integrated intensity maps in different velocity ranges, we subdivided the raw data into two adjacent velocity bins and then applied the maximum entropy program for each velocity range separately. Since the upper and lower velocity ranges are derived from only part of the spectrum, they have slightly different \(\sigma\) values. The \(\sigma\) values for the total, upper, and lower velocity ranges are \(1.04 \times 10^{-5}\), \(0.77 \times 10^{-5}\), and \(0.71 \times 10^{-5}\) erg s\(^{-1}\) cm\(^{-2}\) sr\(^{-1}\), respectively.

4. Results

4.1. Spatial Distribution of the \([\text{C} \\text{II}]\) Emission

We superimposed maps of the total \([\text{C} \\text{II}]\) 158 \(\mu\)m line emission and the emission in the two separate velocity ranges on an optical image (Laustsen, Madsen, & West 1987) of the Antennae (Fig. 1). For a better comparison, we used the same contour levels in each velocity range. The contour levels are in steps of 1 \(\sigma\), deduced from the data of the total velocity range. \(	ext{C}^{+}\) is seen over the full extent of the merging system (Fig. 1a). From the line intensity integrated over the total velocity range, one can infer the origin of the bulk of the \([\text{C} \\text{II}]\) emission. In all of the three images, the peak of the \([\text{C} \\text{II}]\) emission is situated at the interaction zone, with slight differences in the location of the \([\text{C} \\text{II}]\) peak in each velocity range. The distribution of the \([\text{C} \\text{II}]\) emission in the total velocity range (Fig. 1a) and in the upper velocity range (corresponding to the nuclei; Fig. 1b) are very similar and agree well with the overall shape of the galaxy pair as seen in short-exposure optical images, if we take the different beam sizes into account. The emission is elongated along the bridge between the two galaxies, including the interaction zone, NGC 4039, and extends even farther south. It is also extended in the northwest, showing the western loop of \([\text{H} \\text{II}]\) regions around NGC 4038. However, for the upper velocity range one would expect the concentration of the \([\text{C} \\text{II}]\) emission to be stronger at the nuclei and less strong at the interaction zone. Since the cut between the velocity ranges was made at 1550 km s\(^{-1}\) and the velocity range of the gas in the interaction zone is 1450–1590 km s\(^{-1}\) (Amram et al. 1992; Rubin et al. 1970; Stanford et al. 1990), it might be the case that most of the \([\text{C} \\text{II}]\) emission is coming from gas with velocities higher than 1550 km s\(^{-1}\). This would also explain the relatively weak \([\text{C} \\text{II}]\) emission in the lower velocity range. The \([\text{C} \\text{II}]\) emission in the lower velocity range is less extended than that in the other velocity ranges and more concentrated toward the interaction zone, as expected from that velocity. The \([\text{C} \\text{II}]\) peak also coincides with the peak of the CO

Fig. 1.—Integrated \([\text{C} \\text{II}]\) 158 \(\mu\)m intensity map in the velocity ranges of (a) 1420–1740 km s\(^{-1}\), the total \([\text{C} \\text{II}]\) emission; (b) 1550–1740 km s\(^{-1}\), the velocity range containing the 2 nuclei; and (c) 1420–1554 km s\(^{-1}\), the velocity range of the interaction zone, superimposed on an optical image of NGC 4038/9 (Laustsen et al. 1987). The contour levels in all three maps are the same, starting at 1 \(\sigma\) with steps of 1 \(\sigma\) (1.04 \(\times\) 10\(^{-5}\) erg s\(^{-1}\) cm\(^{-2}\) sr\(^{-1}\)). The hatched circle indicates the beam (FWHM of 55\(\arcsec\)). "$S$" indicates the southern clump of the interaction zone in Stanford et al. (1990).
emission of the Antennae (Stanford et al. 1990) (Fig. 2). Within the interaction zone, the southern clump is the strongest CO-emitting region.

4.2. Estimate of the Parameters of the [C II]-Emitting Region

Results of the measurement of the [C II] 158 μm emission in the different velocity ranges for different positions are given in Table 1. The total [C II] luminosity from the region enclosed by the first contour line in Figure 1a is \( L_{\text{[C II]}} = 3.7 \times 10^8 L_\odot \) for the total velocity range. In comparison with the [C II] ISO Long-Wavelength Spectrometer (LWS) observations of the Antennae (Fischer et al. 1996), we determined a line flux of \( \sim 9 \times 10^{-19} \) W cm\(^{-2} \) within the area of the larger ISO beam. This is about 2.4 times higher than the line flux measured with ISO. By weighting the data measured with FIFI within the ISO beam with a Gaussian of 80' FWHM, we obtain a line flux of \( 6.5 \times 10^{-19} \) W cm\(^{-2} \), which agrees within the statistical errors and the calibration errors with the value measured with ISO. One possible explanation for this discrepancy would be if the [C II] emission originates from small clumped regions spread over the interaction zone. Then the emission of clumps at the edge of the ISO beam is only accounted for by the weight of the beam.

The [C II] 158 μm fine-structure line may arise from at least three components of the interstellar medium: photo-
dissociation regions (PDRs), atomic gas clouds, and diffuse H II regions. In starburst galaxies and star-forming regions, the contribution of the [C II] fine-structure line from PDRs is much stronger than from other components of the interstellar medium, which can therefore be neglected. However, it is important to investigate the origin of the [C II] emission from the NGC 4038/9 system. We follow a procedure originally presented in Madden (1993) to investigate the various origins of [C II] emission.

4.2.1. Estimate of the FIR continuum

No FIR continuum map with a resolution comparable to the [C II] data exists for the Antennae. The only FIR continuum data available to compare with the [C II] emission are from IRAS observations. Using the formula given in Lonsdale et al. (1985),

\[
\text{FIR} = 1.26(2.58 \times 10^{-14} S_{60} + 1 \times 10^{-14} S_{100}) \text{ W m}^{-2},
\]

we calculated the FIR luminosity from the IRAS flux densities at 60 \(\mu\)m and 100 \(\mu\)m for the entire Antennae system. With \(S_{60} = 48.68 \text{ Jy}\) and \(S_{100} = 82.04 \text{ Jy}\) (Surace et al. 1993), the FIR luminosity for the total system is \(L_{\text{FIR}} = 3.6 \times 10^{10} \text{ L}_\odot\), with an assumed distance of 21 Mpc. Consequently, the total [C II] luminosity is about 1% of the FIR luminosity. An attempt to obtain sufficient spatial resolution to resolve the nuclei from the IRAS data using HIRES and ADDSCAN was unsuccessful (Surace et al. 1993). Therefore, we use the FIR/radio correlation to get an estimate of the FIR continuum separately for the interaction zone and the nuclei. In general, the FIR/radio correlation is only valid for late-type galaxies; we will use it here, however, because the optical spectra of the nuclei indicate a mixture of H II regions with an old population, and the interaction zone also shows a strong radio continuum (Hummel & van der Hulst 1986) in combination with the young star-forming region. The ISOCAM observations of the 6.7 and 15 \(\mu\)m continuum reveal very clumpy emission dominated by bright knots, and from the good correlation of the 15 \(\mu\)m continuum intensity with the [Ne III]/[Ne II] ratio, Vigroux et al. (1996) deduce that the 15 \(\mu\)m continuum is produced by thermal emission from hot dust heated by the absorption of the ionizing photons emitted by young stars. On the kiloparsec scale of our beam, the extension of the FIR continuum originating from thermal emission from moderately warm dust and the 15 \(\mu\)m continuum created from these young star-forming regions may be similar. Therefore, a strong but very confined recent starburst, as is seen at the interaction zone with ISOCAM, probably does not distort the FIR/radio correlation very much on our kiloparsec scale.

For the whole Antennae, the FIR luminosity and the total flux density of the 20 cm radio continuum, \(S_{1.5 \text{ GHz}} = 486 \pm 20 \text{ mJy}\) (Hummel & van der Hulst 1986), fulfil the FIR/radio correlation:

\[
\log \frac{P_{1.5 \text{ GHz}}}{\text{W Hz}^{-1}} = a \log \frac{L_{\text{FIR}}}{\text{W}} + b,
\]
where $a = 1.30 \pm 0.03$, $b = -25.82$, and $P_{1.5 \text{ GHz}} = S_{1.5 \text{ GHz}} 4\pi R^2$ (Xu et al. 1994). Under the assumption that the FIR/radio correlation is also valid at the scale of our beam size, we estimate the FIR continuum at the interaction zone and the nuclei by distributing the FIR continuum in the same way as the low spatial resolution 20 cm radio continuum (Hummel & van der Hulst 1986) (Fig. 3). For that, we convolved the 20 cm map to a spatial resolution of 55" and scaled it such that the total flux in the map matches the IRAS observation. We obtain a FIR continuum luminosity within our beam of $L_{\text{FIR}} = 2.0 \times 10^{10} L_{\odot}$ at the [C II] peak, $L_{\text{FIR}} = 1.4 \times 10^{10} L_{\odot}$ at NGC 4038, and $L_{\text{FIR}} = 8 \times 10^{9} L_{\odot}$ at NGC 4039.

4.2.2. [C II] Emission From PDRs

For the treatment of PDRs, we used the model described by Stacey et al. (1991, and references therein).

Photodissociation regions are the interfaces between H II regions and molecular clouds where photons with energies less than 13.6 eV escape from the H II regions, dissociate molecules, and ionize elements with dissociation or ionization energies lower than the Lyman limit (13.6 eV). Carbon is the most abundant element with an ionization energy (11.3 eV) less than the 13.6 eV. Ionized carbon is then excited by collisions with electrons and/or atomic and molecular hydrogen. The gas in this region is heated mainly by photoelectric emission from grains illuminated by far-UV radiation. However, most of the far-UV flux absorbed by grains is converted into FIR radiation.

Assuming a high temperature ($T \gg 91$ K), high density ($n > n_{\text{crit}} = 3.5 \times 10^3$ cm$^{-3}$), optically thin [C II] emission, and a beam-filling factor of unity, we can estimate a lower limit of the C$^+$ column density and hydrogen mass (Crawford et al. 1985). Using a solar fractional carbon abundance of [C]/[H] $\sim 3 \times 10^{-4}$ and assuming that all the carbon is in the form of C$^+$, we derive a lower limit of the hydrogen column density. The result of this estimate is given in Table 2. For each of the positions, we took the integrated [C II] intensity in the total velocity range.

| Source                | $M_{\text{min}}(\text{H})$ (10$^2$ $M_{\odot}$) | $N_{\text{min}}(\text{H})$ (10$^{20}$ cm$^{-2}$) |
|-----------------------|-----------------------------------------------|-----------------------------------------------|
| [C II] peak (interaction zone) | 6.8                                           | 2.3                                           |
| NGC 4038              | 3.2                                           | 1.1                                           |
| NGC 4039              | 3.7                                           | 1.3                                           |
| Total galaxy pair     | 18.8                                          | 0.67*                                         |

* Average.
molecular masses given by Stanford et al. (1990) show that the ratio of the mass of the PDR to the molecular mass is 6% for the whole Antennae, 6% for the interaction zone, 4% for NGC 4038, and 15% for NGC 4039. The high ratio for NGC 4039 is probably due to the fact that the beam of the [C II] observation also includes part of the interaction zone. Except for the high ratio in NGC 4039, the PDR to molecular gas mass ratio lies within the expected range of 1%–10% (Stacey et al. 1991).

To compare the [C II] integrated intensity with the CO ($1 \rightarrow 0$) intensity, we use the CO data from Aalto et al. (1995), since their observations were made with a single dish and with a similar beam size, 43” FWHM. They observed three different positions: the interaction zone, NGC 4039, and NGC 4038. For the comparison, we use the [C II] emission in the total velocity range, since the measurement of Aalto et al. (1995) was also obtained in a wide velocity range (~1300 km s$^{-1}$).

In Figure 4, we plot $Y_{[C\ II]} = I_{[C\ II]} / \chi_{\text{FIR}}$ versus $Y_{\text{CO}} = I_{\text{CO}} / \chi_{\text{FIR}}$. The advantage of taking these ratios is that they allow us to determine the gas density, $n_{H}$, and UV field, $\chi_{\text{UV}}$, independently of the beam-filling factor if it is assumed that the [C II], CO, and FIR emission arise from the same regions. Figure 4 also shows theoretically calculated ratios for a set of constant densities $n_{H}$ (solid lines) and a set of constant UV intensities $\chi_{\text{UV}}$ (6 eV $\leq h\nu \leq 13.6$ eV) (thick dashed lines) (Wolfe, Hollenbach, & Tielens 1989; Stacey et al. 1991). The observations for the interaction zone (Fig. 4, filled triangle), NGC 4039 (filled square), and NGC 4038 (filled circle) are marked in the plot. The gray diagonal bars indicate the standard deviation of the FIR luminosity, as derived from the linear regression line of the FIR/radio correlation in Figure 1 of Xu et al. (1994). We use this scatter as an estimate for the error in distributing the total IRAS flux over the mapped area according to the distribution of the 20 cm radio continuum map (see § 4.2.1). The results for the density and the UV intensity are given in Table 3. Two possible solutions for $n_{H}$ and $\chi_{\text{UV}}$ can be found: a low-density (l) and a high-density (h) solution. In both cases, the UV intensity is modest. Under the condition that $\chi_{\text{UV}} < 10^{2}$ (low-density solution) or $\chi_{\text{UV}} / n_{H} < 10^{-3}$ cm$^{-3}$ (high-density solution), a low $I_{[C\ II]} / I_{\text{CO}}$ ratio is predicted (Wolfire 1989). In the low $\chi_{\text{UV}}$ regime, the [C II] emission is reduced by low temperatures ($T < 92$ K), and in the low $\chi_{\text{UV}} / n_{H}$ regime it is reduced by CO self-shielding, which brings the [C II]/CO transition closer to the surface and therefore lowers the C$^{+}$ column density. At the interaction zone, a $^{12}\text{CO}(2-1)/^{12}\text{CO}(1-0)$ line ratio of 1.2 has been observed, which can be interpreted as arising from gas with $n_{H} > 10^{4}$ cm$^{-3}$ (Aalto et al. 1995; see their Fig. 3), supporting the high-density solution in this region. For the nuclei, this ratio has not been observed. The densities we derive for...
the high-density solution are somewhat higher than those derived for Orion, M82, and the inner region of the Galactic Center from the PDR model. However, we find a much lower FUV flux. The FUV flux for the high-density solution is also at the lower limit of the range of the FUV flux derived from the ISO-LWS observations (Fischer et al. 1996). However, Fischer et al. (1996) determined a density for the PDRs that is an order of magnitude smaller than what we derived for the individual positions.

To estimate the beam-filling factor, we used the ratio of the derived $\chi_{\text{FIR}}$ to the modeled $\chi_{\text{UV}}$ (Table 3). If we assume that the beam-filling factor is unity and that most of the stellar photons are absorbed by dust grains, then $\chi_{\text{FIR}} \sim 2\chi_{\text{UV}}$ for B stars and $\chi_{\text{FIR}} \sim \chi_{\text{UV}}$ for O stars. Including the beam-filling factor, $\Phi$, we therefore get $\chi_{\text{FIR}} = (1-2)\Phi\chi_{\text{UV}}$.

For the individual galaxies NGC 4038 and NGC 4039, where a large fraction of late-type stars exists (Bushouse & Werner 1990; Keel et al. 1985), the observed $\chi_{\text{FIR}}$ may be created not only by UV radiation but also from visible light. Thus, taking the beam-filling factor as $\chi_{\text{FIR}}/\chi_{\text{UV}}$ gives an upper limit. But there is still an uncertainty from the estimate of the FIR continuum. From the beam-filling factors, we estimate source sizes of $\approx 24''$ for the interaction zone, which is about the total size of the overlap region observed in CO (Stanford et al. 1990), and $\approx 19''-21''$ for the nuclei, which is about twice the size estimated from radio emission (Hummel & van der Hulst 1986) and from CO observations (Stanford et al. 1990).

From the extinction-corrected hydrogen recombination lines at the interaction zone observed with ISO (Kunze et al. 1996), we can also deduce the UV intensity originating in

### Table 3

| Source                  | PDR Solution | $n_B$ (cm$^{-3}$) | $\chi_{\text{FIR}}$ | $\Phi_{\text{b}}^{\text{c}}$ |
|-------------------------|--------------|-------------------|----------------------|-----------------------------|
| [C II] peak (interaction zone) | l            | $4 \times 10^2$   | 150                  | 0.6                         |
|                         | h            | $1 \times 10^3$   | 460                  | 0.2                         |
| NGC 4038                | l            | $1.4 \times 10^2$ | 120                  | 0.50                        |
|                         | h            | $2 \times 10^3$   | 500                  | 0.1                         |
| NGC 4039                | l            | $3 \times 10^2$   | 80                   | 0.45                        |
|                         | h            | $1 \times 10^3$   | 240                  | 0.15                        |

* Solution notations: l: low-density solution; h: high-density solution.

In units of $J_0 = 2 \times 10^{-4}$ erg s$^{-1}$ cm$^{-3}$ sr$^{-1}$ (Draine 1978).

$^c$ Beam-filling factor: $\Phi_{\text{b}} = \chi_{\text{FIR}}/\chi_{\text{UV}}$. 

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**Fig. 4.—** Ratios $Y_{[\text{C II}]} = I_{[\text{C II}]}/\chi_{\text{FIR}}$ vs. $Y_{\text{CO}} = I_{\text{CO}}/\chi_{\text{FIR}}$. The solid lines represent a set of constant densities, and the dashed lines a set of constant UV intensities characteristic of PDRs (Stacey et al. 1991). The filled triangle marks the observations at the [C II] peak, the filled square at NGC 4039, and the filled circle at NGC 4038. The gray diagonal bars indicate the standard deviation of $\chi_{\text{FIR}}$. 

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this region. An equivalent single-star effective temperature of the stellar ionizing radiation field of 44000 K has been derived from the \([\text{Ne}^\text{ii}]\) 15.6 \(\mu\text{m}/[\text{Ne}^\text{ii}]\) 12.8 \(\mu\text{m}\) line ratio (Kunze et al. 1996). This effective temperature corresponds to an O5 main-sequence star. Therefore, we use the properties of such a star to derive the Lyman continuum emission. About 60\% of the total stellar luminosity is emitted in the Lyman continuum, with an average photon energy of 18 eV (Panagia 1973). The rest is mainly emitted as far-UV radiation. Assuming case B recombination (Osterbrock 1989), we get for the relation between the extinction-corrected Br\(\alpha\) line intensity (Kunze et al. 1996) and the UV intensity, 

\[
I_{\text{UV}} = I_{\text{Br}\alpha} \frac{h}{\lambda_{\text{Br}\alpha}} \int_4^{+} \frac{\alpha_{n-m}}{\alpha_{4-2}} \left( \frac{\pi}{2} \right) \frac{D_4}{D_3} \frac{1}{\sqrt{T}} \frac{E_4}{E_3} \frac{E_{\text{Br}\alpha}}{E_{\text{H}^\star}} \Phi_d \, \text{erg} \, \text{s}^{-1} \, \text{cm}^{-2} \, \text{sr}^{-1},
\]

where \(j_{4-3}/j_{4-2}\) is the relative intensity of Br\(\alpha\) to H\(\beta\), \(\alpha_{n-m}\) is the total recombination coefficient, and \(\alpha_{4-2}\) is the effective recombination coefficient of H\(\beta\) from Hummer & Storey (1987). From this expression, we derive a UV intensity of \(I_{\text{UV}} = 345X_{\odot}\) (for standard conditions \(T = 10^4\) K, \(n = 10^4\) cm\(^{-3}\)) and thus a far-UV intensity of \(I_{\text{UV}} = 230X_{\odot}\) (\(\chi_{\text{UV}} = 230\)), which is comparable to the far-UV we obtained from the \(Y_{\text{CII}}\) vs \(T_{\text{eff}}\) plot for the interaction zone. We have made this estimate for the interaction zone only, since ISO has only measured the hydrogen lines in the interaction zone.

4.2.3. [C\(\text{II}\)] From the Cold Neutral Medium and/or Warm Neutral Medium

In the neutral interstellar medium, ionized carbon is excited by collisions with electrons and atomic hydrogen. The integrated intensity one would expect through collisions can be estimated by (see also Madden et al. 1993, 1997)

\[
I_{\text{C II}} = 4\pi \frac{h \nu A}{4\pi} \left[ \frac{2}{1 + 2 \exp(-91/T)} + \frac{n_{\text{H},\text{crit}}/n_{\text{H}}}{\exp(-91/T)} \right] \frac{X_{\text{C II}}}{X_{\odot}} \Phi_d,
\]

where \(h\) is Planck’s constant, \(\nu\) is the frequency of the transition, \(A\) is the Einstein coefficient for spontaneous emission, \(2.29 \times 10^{-6}\) s\(^{-1}\) (Nussbaumer & Storey 1981), \(T\) is the temperature, \(n_{\text{H}}\) is the density of atomic hydrogen, and \(X_{\text{C II}}\) is the ionization fraction of the medium. We assume that the carbon abundance is solar and that all the carbon is in the form of C\(^+\) \((X_{\text{C II}} \approx 3 \times 10^{-4})\). We used the peak value of the column density \((N_{\text{H}})\) plot of van der Hulst (1979; see their Fig. 5), \(N_{\text{H}} \approx 6.3 \times 10^{20}\) cm\(^{-2}\). The beam-filling factor was assumed to be 1. The critical density for collisions with atomic hydrogen, \(n_{\text{H},\text{crit}}\), is deduced from the cooling function for collisional excitation of [C\(\text{II}\)] by atomic hydrogen (Launay & Roueff 1977), and that for collisions with electrons, \(n_{e,\text{crit}}\), is deduced from collision strengths for [C\(\text{II}\)] collisions with electrons (Blum & Pradhan 1992), and fitted as a function of temperature.

The warm neutral medium (WNM) in the Galaxy is characterized by a low density, \(n_{\text{H}} \approx 1\) cm\(^{-3}\), and temperatures in the range \(T \sim 4 \times 10^3\) to \(8 \times 10^3\) K, with an ionization fraction of \(X_{\text{C II}} \sim 3 \times 10^{-2}\) (Kulkarni & Heiles 1987, 1988). The density in this medium is far below the critical densities for collisions of [C\(\text{II}\)] with electrons and atomic hydrogen.

Thus, every collisional excitation will lead to radiative deexcitation. In this regime, a maximum possible integrated [C\(\text{II}\)] intensity of \(I_{\text{C II}} \sim 1 \times 10^{-6}\) erg s\(^{-1}\) cm\(^{-2}\) sr\(^{-1}\) (at \(T = 4 \times 10^3\) K, \(n_{\text{H}} = 1\) cm\(^{-3}\)) is estimated for collisions with both electrons and atomic hydrogen, and both collision partners contribute roughly equally to the integrated intensity. This estimated value is almost 2 orders of magnitude lower than the integrated intensity observed at the [C\(\text{II}\)] peak, which coincides roughly with the peak of the H\(\alpha\) column density. Since this estimated [C\(\text{II}\)] integrated intensity is also more than 1 order of magnitude smaller than the observed integrated intensity in the nuclei, where the H\(\alpha\) column density should be smaller (van der Hulst 1979), a contribution of [C\(\text{II}\)] emission from the WNM to the observed integrated intensity is negligible.

Carrying out the same calculations for a cold neutral medium (CNM) characterized by \(T \sim 50–100\) K, \(n_{\text{H}} \sim 50–200\) cm\(^{-3}\), and an ionization fraction of \(X_{\text{H}} \approx 5 \times 10^{-4}\) (estimated for the Galaxy; Kulkarni & Heiles 1987, 1988) and again using the peak column density of \(N_{\text{H}} \approx 6.3 \times 10^{20}\) cm\(^{-2}\) (van der Hulst 1979), we get a maximum integrated intensity of \(I_{\text{C II}} \approx 2.7 \times 10^{-5}\) erg s\(^{-1}\) cm\(^{-2}\) sr\(^{-1}\) (at \(T = 100\) K, \(n_{\text{H}} = 200\) cm\(^{-3}\)) and a minimum integrated intensity of \(I_{\text{C II}} \approx 3.0 \times 10^{-6}\) erg s\(^{-1}\) cm\(^{-2}\) sr\(^{-1}\) (at \(T = 50\) K, \(n_{\text{H}} = 50\) cm\(^{-3}\)) for collisions with electrons and atomic hydrogen, where the contribution of collisions with electrons can almost be neglected. Therefore, at standard conditions \((T = 70\) K, \(n_{\text{H}} = 100\) cm\(^{-3}\)), the [C\(\text{II}\)] emission from CNM is a factor of 9 smaller than the total [C\(\text{II}\)] radiation at the interaction zone, but may contribute as much as \(~1/3\) of the total [C\(\text{II}\)] emission. For the nuclei, we estimate a similar contribution from CNM to the [C\(\text{II}\)] radiation using a H\(\alpha\) column density of \(~3.5 \times 10^{20}\) cm\(^{-2}\), from Figure 5 of van der Hulst (1979), at the positions of the nuclei.

4.2.4. [C\(\text{II}\)] From Ionized Gas

Another possibility for the origin of the [C\(\text{II}\)] emission is in ionized gas, either extended low-density warm ionized medium (ELDWIM) or “standard” H\(\alpha\) regions.

Although the shape of the contour plot of the [C\(\text{II}\)] fine-structure line (of the total velocity range) shows some similarities to the low-resolution 20 cm radio continuum (Hummel & van der Hulst 1986) (Fig. 3), this extended radio continuum has a relatively steep radio spectrum \((\alpha < -0.8)\), and hence is almost completely nonthermal and does not trace extended ionized regions. The radio spectrum is steepest in the eastern part of the system, and regions devoid of strong optical emission, e.g., at the location of the dust patch in between the galaxy nuclei, show steeper spectra than regions that are bright in Hz and blue light. Therefore, the ELDWIM probably plays only a minor role, and [C\(\text{II}\)] emission from this medium may be neglected.

However, the radio knots 1–13 seen in the 4.9 GHz high-resolution map of Hummel & van der Hulst (1986) (Fig. 5) have a sizeable thermal component. To estimate the [C\(\text{II}\)] intensity expected to arise from the thermal emission of the knots within our beam, we weight them relative to their distance from the center of the beam. We calculated the emission measure (Spitzer 1978) to be EM = 1250 cm\(^{-6}\) pc for the interaction zone and EM = 270 and 690 cm\(^{-6}\) pc for NGC 4038 and NGC 4039, respectively. Making the crude approximations that all of the carbon in the H\(\alpha\) region is in the form of C\(^+\) and that all of the observed EM results in
FIG. 5.—4.9 GHz continuum map of Hummel & van der Hulst (1986) (white contours) superimposed on the [C II] integrated intensity map of the total velocity range (black contours). The FWHM of the [C II] beam, indicated by the hatched circle, is 55''; the HPBW of the radio map is 6'. The numbers 1–13 indicate the discrete radio knots (Hummel & van der Hulst 1986). The gray area represents the area covered by the arrays.

the excitation of [C II], the expected [C II] integrated intensity is

\[ I_{[\text{C} \, \text{II}]} = \frac{h \nu A}{4 \pi n_{\text{crit}}} \left[ \frac{g_u / g_l}{1 + (1 + g_u / g_l)(n_e / n_{\text{crit}})} \right] X_{\text{C}^+ , \text{EM}} , \]

where \( g_u / g_l = 2 \) is the ratio of the statistical weights in the upper and lower levels and \( n_{\text{crit}} = 49 \) cm\(^{-3}\) is the critical density of C\(^+\) for collisions with electrons at 10\(^4\) K (Blum & Pradhan 1992). Assuming an electron density of \( n_e = 300 \) cm\(^{-3}\), as estimated from the extinction-corrected ratio of the [S III] 18.71 \( \mu \)m/33.48 \( \mu \)m fine-structure lines (Kunze et al. 1996), the expected [C II] intensity is \( \sim 5.6 \times 10^{-6} \) erg s\(^{-1}\) cm\(^{-2}\) sr\(^{-1}\) at the interaction zone, which is about a factor of 20 smaller than the observed [C II] intensity in the lower velocity range. For the nuclei, we assume an electron density of \( n_e = 100 \) cm\(^{-3}\) (Rubin et al. 1970), and obtain expected [C II] intensities of \( I_{[\text{C} \, \text{II}]} = 3.3 \times 10^{-6} \) and \( 8.4 \times 10^{-6} \) erg s\(^{-1}\) cm\(^{-2}\) sr\(^{-1}\) for NGC 4038 and NGC 4039, respectively. This is about a factor of 17 lower for NGC 4038 and a factor of 8 lower for NGC 4039 than the observed [C II] intensities at the upper velocity range. However, most of the carbon in H II regions is probably in the form of C\(^++\) rather than C\(^+\). Therefore, the contribution of the [C II] emission expected from H II regions is even lower, and should be only a minor fraction of the observed [C II] radiation.

5. DISCUSSION

As shown in the previous section, the possible contribution of [C II] emission from the WNM, ELDWIM, and H II regions to the total observed [C II] emission is small. For high temperatures and high densities, a contribution of [C II] emission from CNM may become important. However, since at standard conditions of the CNM a contribution of [C II] emission to the observed [C II] emission is also small, we will only consider PDRs as the origin of the [C II] emission in the following discussion.

Stacey et al. (1991) demonstrated the utility of the [C II]/CO(1–0) ratio to distinguish between starburst activity in galaxies and more quiescent regions. They find [C II]/CO \( \sim 6100 \) (4000)\(^6\) for starburst nuclei and Galactic star-forming regions, while the more quiescent regions show a ratio of \( \sim 2000 \) (1300).\(^4\) We find [C II]/CO \( \sim 2350 \) (1650)\(^5\) toward the [C II] peak (overlap region) and 1650 to 1800 (1150 to 1250)\(^5\) toward the nuclei, implying that there is no strong starburst activity taking place, given the resolution of our data. These ratios are more consistent with quiescent spiral galaxies, e.g., NGC 891 and NGC 3628 (Stacey et al. 1991).

\(^4\) CO data (NRAO) corrected for main beam efficiency (\( \sim 0.65 \)).

\(^5\) CO data (SEST) corrected for main beam efficiency (\( \sim 0.7 \)).
However, observations with ISO (Kunze et al. 1996; Fischer et al. 1996; Vigroux et al. 1996), CO observations (Stanford et al. 1990; Aalto et al. 1995), and observations of the radio continuum (Hummel & van der Hulst 1986) indicate ongoing strong star formation activity in the interaction zone. A comparison of the CO flux of the interferometric observation (scaled to the size and position of the single-dish observation) of Stanford et al. (1990) (Fig. 2) with the single-dish observation of Aalto et al. (1995) show a factor of ~4 more CO flux in the single-dish observation (F_Co) for the interaction zone and NGC 4039 and a factor of 3 more for NGC 4038. If we assume that 1/3 of the single-dish CO flux at the interaction zone arises from a confined starburst region, F_Co/F_Co = 6000 (the mean ratio observed for starburst galaxies; Stacey et al. 1991) for this region, we find a ratio of (F_Co/F_Co - F_Co)/F_Co ≈ 1200 for an underlying component. For F_Co/F_Co, we used the observed ratio of 2350. This estimate suggests that the [C II] emission toward the interaction zone can also be explained by a two-component model with a confined starburst region and a quiescent surrounding molecular cloud system. Making the same estimate for NGC 4039, we get a [C II] to CO ratio of 400 for an underlying component. To make the same estimate for NGC 4038, one must assume a lower [C II] to CO ratio, integrated intensity ratio for the confined starburst region, since otherwise the ratio of the underlying component becomes negative. The lowest value for the [C II] to CO ratio in Stacey et al. (1991) is 340 for the Sgr A + 20 km s⁻¹ cloud. If we assume a lower limit of 300 for the [C II] to CO ratio for the underlying component, we find a maximum [C II] to CO ratio of 4400 for a confined starburst region for NGC 4038, using the observed ratio of F_Co/F_Co = 1650. From this estimate, we find that enhanced star-forming activity in NGC 4039 and a moderate activity in NGC 4038 could be explained by the data. This interpretation would be consistent with the results of the mid-infrared observations of NGC 4038/9 made with ISO/CAM (Vigroux et al. 1996). These show that the most active star formation in the Antennae system occurs in the overlap region, and within that region in a confined area (knot 2 in Fig. 5; knot A in Fig. 1 of Vigroux et al. 1996), coinciding with the southern clump of the CO emission in Stanford et al. (1990). The ISO-SWS observations of the interaction zone can also be described by a young (≈ 7 x 10⁶ yr) starburst with an IMF extending up to 100 M☉ (Kunze et al. 1996). The interpretation that the [C II] emission arises from confined small star-forming regions is also consistent with the detection of H II regions in the interaction zone (Fischer et al. 1996). The scenario in which most of the [C II] emission comes from confined star-forming regions supports the PDR model with a small beam-filling factor and therefore with high density. The PDR solution with high density is also supported by the ISO observations of Fischer et al. (1996).

Although we see moderate [C II] emission from the H II regions in the western loop around NGC 4038, in the absence of CO data for that region and taking our beam size into account, we cannot draw a conclusion about the star-forming activity there.

Just recently, Mirabel et al. (1998) published a contour map of the mid-infrared continuum distribution of the Antennae system. The contour map shows that the main peak of the mid-infrared continuum is at an off-nucleus position that is inconspicuous at optical wavelengths. Mirabel et al. (1998) argue that the main peak of the mid-infrared continuum reveals the most intense starburst in a region that is heavily obscured in the optical wavelength range. The [C II] peak, located at the dust patch in between the galaxies, is offset from the main peak of the mid-infrared emission. Since the majority of the [C II] emission arises from PDRs, the [C II] peak discloses star formation regions that are totally obscured in the optical and even in the mid-infrared regime. In this respect, it is interesting that the peak of the [C II] emission also does not coincide with the peak of the 100 μm and 160 μm continuum emission presented in the recent publication of Bushouse, Telesco, & Werner (1998).

6. CONCLUSION

We present a map of NGC 4038/9 in the [C II] 158 μm fine-structure line. [C II] emission is detected over the optical extent of the system of galaxies and peaks at the interaction zone. The total luminosity of the [C II] line is 3.7 x 10⁸ L☉, which is about 1% of the FIR luminosity of the Antennae. Only a negligible fraction of the observed [C II] emission can originate in the WNM if conditions are similar to those in Galactic atomic clouds. Under normal conditions, the [C II] emission from standard CNM makes only a small contribution to the total [C II] emission; however, it may rise to 1/3 of the total [C II] emission for individual positions. Only minor fractions of the [C II] emission at the interaction zone and the nuclei can arise from H II regions. PDRs are the dominant source for the [C II] emission. We estimate minimum hydrogen masses associated with the [C II] emitting region of 1.9 x 10⁵ M☉ for the entire merging system and 6.8 x 10⁵ M☉, 3.2 x 10⁵ M☉, and 3.7 x 10⁴ M☉ within one beam centered at the interaction zone, NGC 4038, and NGC 4039, respectively. Assuming a single emission component in the beam, we derive a density of the [C II]-emitting gas in PDRs of 1 x 10³ cm⁻³ for the interaction zone and 2 x 10³ cm⁻³ and 1 x 10⁴ cm⁻³ for NGC 4038 and NGC 4039, respectively, and far-UV intensities of 460 Φ₀ for the interaction zone, 500 Φ₀ for NGC 4038, and 240 Φ₀ for NGC 4039. The derived beam-filling factor of the emission from the PDRs is 20% for the interaction zone and 10%–15% for the nuclei. However, the PDR model also allows a solution with a low density (~10² cm⁻³), high beam-filling factor (~50%), and low FUV intensity (~100 Φ₀). The low beam-averaged [C II]/CO ratio of 2350 toward the interaction zone and the even lower ratios at the nuclei indicate that no global starburst is occurring either in the area surrounding the interaction zone or in the nuclear regions. The high-excitation lines observed with ISO-SWS, which trace the starburst, must therefore arise from a small, confined region in the interaction zone. This result is also supported by the observations with ISO/CAM. Therefore, on the scale of our [C II] beam, a single emission component for the PDR is only a crude approximation. Using interferometric and single-dish CO observations and expected [C II]/CO ratios for starburst regions and quiescent clouds, we constructed a two-component model consisting of a confined starburst region and molecular clouds enveloping the starburst. From this model, we find that the [C II] emission at the interaction zone originates partly from confined starburst regions and partly from surrounding quiescent clouds. If we apply this model to the nuclei, we also get enhanced star formation activity in NGC 4039, with a low [C II]/CO ratio for the...
quiescent clouds but only moderate star-forming activity in NGC 4038. This two-component model supports the high-density solution for the PDRs.

Future investigation of the Antennae in the $\text{[N}\,\text{II]}$ 205 μm fine-structure line would be very helpful to further disentangle the origins of the $\text{[C}\,\text{II]}$ line. In addition, observations at higher spatial resolution in the FIR regime (e.g., with the Far-Infrared and Submillimeter Telescope [FIRST] and the Stratospheric Observatory for Infrared Astronomy [SOFIA]) would be a great step forward in investigating this and other spatially very complex objects in more detail.

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