H I AND OH ABSORPTION TOWARD NGC 6240

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ABSTRACT

VLA observations of large-scale H I and OH absorption in the merging galaxy of NGC 6240 are presented with 1" resolution. H I absorption is found across large areas of the extended radio continuum structure with a strong concentration toward the double nucleus. The OH absorption is confined to the nuclear region. The H I and OH observations identify fractions of the gas disks of the two galaxies and confirm the presence of central gas accumulation between the nuclei. The data clearly identify the nucleus of the southern galaxy as the origin of the symmetric superwind outflow and also reveal blueshifted components resulting from a nuclear starburst. Various absorption components are associated with large-scale dynamics of the system including a foreground dust lane crossing the radio structure in the northwest region.

Subject headings: galaxies: ISM — galaxies: nuclei — galaxies: starburst — ISM: molecules — masers

1. INTRODUCTION

The chaotic appearance of NGC 6240 at all wavelengths is due to a forceful galactic collision of two galaxies (Fosbury & Wall 1979). The two individual nuclei of NGC 6240 were first detected in R and I bands at a projected distance of 1.8" or 0.9 kpc (Fried & Schulz 1983). Early Hα observations extended emission with two independent and almost perpendicular disk systems (Bland-Hawthorn et al. 1991).

NGC 6240 is a prototypical luminous infrared galaxy with an IR luminosity of \( L_{IR} = L_{8-1000\,\mu m} \approx 6 \times 10^{11} L_\odot \) (Sanders et al. 1988). The far-IR (FIR) luminosity of these galaxies is powered by extremely high star formation activity and/or an embedded active galactic nucleus (AGN). For NGC 6240 the mid-IR observations are consistent with a dominant starburst power contribution of approximately 75% within the central 5 kpc (Genzel et al. 1998).

Radio data show two nuclei embedded in a connecting structure that extends into a loop structure to the west (Condon et al. 1982; Colbert et al. 1994) also seen in our continuum data (see Fig. 1). MERLIN and the Very Long Baseline Array (VLBA) observations of the two nuclear continuum sources show brightness temperatures of \( 7 \times 10^6 \) K for the northern source and \( 1.8 \times 10^7 \) K for the southern source (Gallimore & Beswick 2004). The inverted spectra at low frequency confirm the AGN nature at each of the nuclei. The loop results most likely from a bubble front swept up by a superwind emanating mostly from the southern nucleus (designated as N1 in Fig. 1; Colbert et al. 1994; Ohyama et al. 2000). NGC 6240 exhibits H I and OH absorption against the nuclear continuum (Baan et al. 1985). Recent H I absorption studies at 0.3" resolution with MERLIN distinguish the absorption at each of the two nuclear components (Beswick et al. 2001).

ASCA, XMM-Newton, and Chandra data confirm the presence of two deeply buried AGNs in the NGC 6240 system on the basis of a hard X-ray component with neutral Fe Kα lines in addition to the soft X-ray components due to the starburst (Iwasawa & Comastri 1998; Boller et al. 2003; Komossa et al. 2003). The most prominent AGN is located at the southern nucleus N1, where the obscuration is the highest. The extended X-ray emission has a close correlation with the well-known (butterfly-shaped) Hα emission. Hα studies with HST confirm the presence of filamentary structures filling the inner volume of the arc and confirm the presence of confining walls of the outflow at either side of the nucleus (Gerssen et al. 2004). Significant Hα structures have also been found in NGC 6240 in the form of a butterfly-shaped structure that partially superposes the radio arc and extended radio structure.

NGC 6240 displays strong H2 1-0 S(1) and [Fe II] line emission that peaks between the stellar light of the nuclei but lies closer to the southern nucleus (van der Werf et al. 1993; Joseph & Wright 1985; Ohyama et al. 2000). Spectroscopic studies of H2 at K band allow the separation of the dynamics of the two nuclei (Tecza et al. 2000). The near-IR (NIR) light of each of the nuclei is dominated by red supergiants formed during a short episode of intense star formation 15–25 million years ago. K-band infrared imaging with Keck II and NICMOS on HST has revealed elongated structures at both the north and south nuclei and considerable substructure within each nucleus (Max et al. 2005). Additional pointlike regions are found around the two nuclei, which are thought to be young super star clusters.

CO(2–1) emission studies with the IRAM interferometer show a similar structure as the H2 emission and also peaks between the two nuclei (Tacconi et al. 1999). Most of the CO flux is
This paper presents studies of the OH and H\textsc{i} absorption in the NGC 6240 system using the NRAO Very Large Array (VLA) in A-Configuration. With NGC 6240 at a distance of 104 Mpc the spatial conversion for the VLA data is 504 pc arcsec\(^{-1}\), which complements the resolution of other spectral line and continuum studies. Our data reveal more of the dynamics of the system and provide connections to studies of other atomic and molecular emissions.

2. OBSERVATIONS

Observations of the H\textsc{i} 21 cm line and the OH main lines at 1665 and 1667 MHz toward NGC 6240 were made on 1995 September 1, with the NRAO Very Large Array in the A-configuration. Phase tracking was centered on \(\alpha = 16^h50^m28.3^s\), \(\delta = 02^d28^m53^s\) (B1950).

The H\textsc{i} line was observed using a two-IF (intermediate frequency) mode, each IF having a bandwidth of 6.25 MHz subdivided into 32 channels of 195.3 kHz in width. This setup resulted in a usable velocity coverage of 1298 km s\(^{-1}\) and a velocity resolution of 43.3 km s\(^{-1}\). The spatial resolution in the H\textsc{i} spectral data is 1.95\(''\) \times \ 1.79\(''\) for natural (NA) weighting, and the channel width is 43.3 km s\(^{-1}\). The rms in the individual channel maps is 0.49 mJy beam\(^{-1}\).

Both OH lines at 1665 and 1667 MHz were observed simultaneously using two partially overlapping IFs of width 6.25 MHz with 32 channels of width 195.3 kHz. The synthesized band used for this discussion has a center frequency of 1666.38 MHz (between those of the 1665 and 1667 MHz lines) and has a total velocity coverage of 1326 km s\(^{-1}\). The velocity scale in this presentation is heliocentric in the optical definition and has been regressed using the rest frequency of the 1667 MHz line. The resolution in the OH maps is 1.11\(''\) \times \ 1.08\(''\), and the channel width is 36.7 km s\(^{-1}\). The rms in the channel maps is 0.41 mJy beam\(^{-1}\).

Continuum maps at 21 and 18 cm have been constructed using line-free channels. The rms and the beam size of the two maps are, respectively, 0.46 mJy beam\(^{-1}\) with 1.965\(''\) \times \ 1.79\(''\) and 0.28 mJy beam\(^{-1}\) with 1.11\(''\) \times \ 1.08\(''\).

The data were reduced using the NRAO software package AIPS. The flux and bandpass calibrator and phase calibrator were 3C 286 and 1648+015 for both H\textsc{i} and OH line data sets. Image cubes were made with a pixel size of 0.3, using a variety of weighting schemes. Continuum data sets were constructed by averaging line-free channels. Subtraction of the continuum was done independently in the visibility and image domains, resulting in consistent results. In the case of the OH data both IFs were imaged independently and joined after the continuum subtraction, averaging overlapping channels. Due to the uncertainty of the baseline structure at the edges of the spectrum, we estimate a flux uncertainty of 20% for the OH absorption data and 10% for the H\textsc{i} absorption and the continuum data.

3. RESULTS

The distance of NGC 6240 is assumed to be \(D = 104\) Mpc for a systemic optical velocity of 7275 km s\(^{-1}\) using \(H_0 = 70\) km s\(^{-1}\) Mpc\(^{-1}\). At this distance the spatial conversion is 504 pc arcsec\(^{-1}\).

In the discussions below, we have adopted the radio designations of Colbert et al. (1994) for the nuclei N1 and N2 and the components of NGC 6240. In addition, the suggestion has been made for the northern component N3, which may be a third nucleus or an enhanced fragment of the northern galaxy. There is a southern extension (S) and various western components (W1–W4) forming the arc structure of 5.9 kpc in size. A W0 component has been designated in the continuum structure to the west of N3. These designations have been indicated in Figure 1 (bottom).

concentrated in a thick and turbulent disklike structure between the two IR/radio nuclei. Studies with Nobeyama Rainbow interferometer (Hagiwara 1998) indicate that the HCN(1–0) and HCO\(^+\) fluxes also peak between the nuclei, and do not coincide with the star-forming region in the galaxy (Nakanishi et al. 2005). The molecular structure accounts for a large fraction (30%–70%) of the dynamic mass. Although the central location of the molecular material in NGC 6240 is not unique, it is notably different from the (more advanced) interaction in Arp 220, where the emission peaks at the two nuclei (Scoville et al. 1997; Sakamoto et al. 1999).
3.1. Continuum Studies

Contour maps of the natural-weighted continuum emission at 1420 MHz and the robust-weighted continuum emission at 1666 MHz are presented in Figure 1. The integrated flux densities in the maps are 466 and 333 mJy, with peak values of 108 and 58 mJy, respectively. Our A-array L-band images are consistent with previous B-array images except that our peak fluxes are higher by 10%–20%, when convolved to a resolution of 4.79” × 4.39” of Colbert et al. (1994), possibly due to slightly different integration boxes. The 21 cm map shown in Figure 1 (top) is optimized for the detection of extended low-brightness features and shows that the individual radio components N1 (south) and N2 (+N3) (north) are embedded in a halo of diffuse emission. The higher resolution 18 cm map in Figure 1 (bottom) clearly separates the two nuclei N1 and N2 (+N3). At higher resolution the N1-N2 axis is found to be at P.A. = 20° with a (projected) separation of the nuclei of 1.575” or 93 pc (Hagiwara et al. 2003; Gallimore & Beswick 2004).

The structure along the western arm (W1 – W4) shows diffuse emission without any sharp peaks at this resolution. The new components NW and W0 have been added to indicate the diffuse structure west of N3. Diffuse extensions can be seen in the northeast (NE), the southeast (SE), and south (S). We present radio continuum parameters derived from the 1666 MHz map in Table 1.

The large-scale continuum structure shows a strong similarity to the butterfly structure found in the optical and X-ray (Komossa et al. 2003). The primary cause of this structure would be a nuclear blowout from the nuclear region of N1 in the southern galaxy. The large-scale Hα structure toward the west (see Max et al. 2005) appears to match and complement the loop structure in the radio. In addition, there eastern complement to the western loop in Hα and soft X-ray (Max et al. 2005; Komossa et al. 2003). The SE and NE radio extensions agree with X-ray and Hα structures.

3.2. The H I Absorption

The H I line characteristics.—The H I absorption spectra in the extended emission region of NGC 6240 have been given in Figure 2. The profiles of the H I absorption at the two nuclei are very similar as both spectra have a full width at zero intensity of about 900 km s⁻¹ and a half-power width of about 348 km s⁻¹. However, the absorption at N2 is 1.7 times stronger than the absorption at N1, and the line at N2 is more symmetric than the N1 line that is skewed due to a higher velocity component. The systemic velocities at N1 and N2 are 7295 and 7339 km s⁻¹, respectively. N1 lies just south of the peak in the H I absorption column density in Figure 2.

The spectra presented in Figure 2 indicate that there are large differences in the absorption columns and that absorption is seen over a velocity range of more than 900 km s⁻¹. This velocity width results from the rotation in each of the galaxies, the orbital velocity component of the two galaxies, and the inflow and outflow due to the interaction. The line of sight to each nucleus does not provide an accurate estimate of the systemic velocity of that nucleus. The spatial resolution of the 21 cm data is 980 × 900 pc, and our line of sight toward the two nuclei will sample multiple velocity components. The high-resolution H I absorption study with MERLIN at 0.3” resolution by Beswick et al. (2001) revealed two isolated absorption components at the locations of the N1 and N2 nuclei at velocities 7087 and 7260 km s⁻¹ (radio definition). Using the optical heliocentric definition, we find systemic velocities $V(N1) = 7258$ and $V(N2) = 7440$ km s⁻¹, and we adopt these as a more accurate approximation of the systemic velocities of the two nuclei. It should be noted that these velocities straddle the absorption peak in the two nuclear absorption spectra of Figure 2. While the peak of the absorption column density coincides with N1, the centroid absorption velocity at N1 is about 100 km s⁻¹ lower, due to the lower velocity of the structural component between the nuclei.

The H I PV diagrams.—Figures 3 and 4 present velocity-position maps in two principal east-west and north-south directions. These diagrams cover only the double-nucleus region. The R.A.–velocity diagrams of Figure 3 show the velocity structure in the south and the north of the system. Close to N1 where the column density peaks at 7265 km s⁻¹, the rotation is essentially south to north, with a gradient to be determined from the position-velocity (PV) plot along the declination axis. In the northern PV diagram, the extended absorption peaks just south of N2 at 7385 km s⁻¹ and shows an west-to-east velocity gradient of 1.0 km s⁻¹ pc⁻¹ close to N2. In the north, an additional (weak)

| COMPONENT   | α (B1950) | δ (B1950) | $L_\alpha$ (mJy beam⁻¹) | $S_\alpha$ (mJy) | $L_\delta$ (mJy beam⁻¹) | $S_\delta$ (mJy) |
|-------------|-----------|-----------|--------------------------|----------------|--------------------------|----------------|
| N1          | 16 50 27.84 | 02 28 57.5 | 108.8                    | 225.9          | 55.7                     | 88.2          |
| N2 + N3     | 16 50 27.84 | 02 28 58.7 | ...                      | ...            | 41.4                     | 74.1          |
| NW          | 16 50 25.70 | 02 29 00.2 | 6.03                     | ...            | 3.3                      | 6.3           |
| W0          | 16 50 27.43 | 02 29 02.3 | 15.77                    | 15.5           | 6.1                      | 24.0          |
| W1          | 16 50 27.18 | 02 29 02.6 | 6.65                     | ...            | 3.4                      | 6.4           |
| W2          | 16 50 27.16 | 02 29 00.2 | 13.8                     | 14.1           | 5.2                      | 16.4          |
| W3          | 16 50 26.92 | 02 28 56.6 | 11.1                     | ...            | 4.4                      | 14.4          |
| W4          | 16 50 27.20 | 02 28 55.1 | 9.8                      | 9.7            | 4.4                      | 12.1          |
| S           | 16 50 27.78 | 02 28 53.3 | 14.6                     | 13.8           | 6.2                      | 17.9          |
| E1          | 16 50 28.20 | 02 28 57.1 | 1.5                      | ...            | ...                      | ...           |
| NE          | 16 50 28.08 | 02 28 59.0 | 1.8                      | ...            | ...                      | ...           |
| SE          | 16 50 27.90 | 02 28 55.1 | 4.0                      | 5.7            | ...                      | ...           |

Notes.—Units of right ascension are hours, minutes, and seconds, and units of declination are degrees, arcminutes, and arcseconds. The 21 and 18 cm continuum maps have an rms of 0.30 and 0.27 mJy beam⁻¹, respectively.
second component appears at 7700 km s$^{-1}$ with an east-to-west velocity gradient of 0.53 km s$^{-1}$ pc$^{-1}$. The extended low-declination outflow structure south of N1 reaches 6900 km s$^{-1}$ (Fig. 3, bottom) and has a southwest-northeast gradient of 0.89 km s$^{-1}$ pc$^{-1}$.

The declination-velocity diagrams of Figure 4 display three velocity profiles along the east side, close to the center, and the west side of the central region (along a south-north R.A. direction). The diagrams show a changing south-north velocity gradient resulting from three distinct components. South of N1 there is a gradient of 1.49 km s$^{-1}$ pc$^{-1}$; north of N2, a gradient of 1.15 km s$^{-1}$ pc$^{-1}$; and between N1 and N2, a gradient of 0.26 km s$^{-1}$ pc$^{-1}$, which is close to the predicted value of 0.24 km s$^{-1}$ pc$^{-1}$ based on the velocity difference of the two nuclei. This central component is dominated by an accumulation of gas in between the two nuclei. A similar absorption structure is found in the OH data. In accordance with Figure 3, an east-west component enters between 7300 and 7750 km s$^{-1}$, which occurs at high declination at the west side (right side of frame) of the source, i.e., going toward the NW region and possibly representing streaming gas motions in the northern galaxy. A number of rather marginal but distinctly offset components are found west of N2 (Fig. 4, left) and southeast of N2 (Fig. 3, top), covering a large velocity range of 7000–7750 km s$^{-1}$.

In our discussion of the OH absorption data below, we will correlate our findings of the H$\alpha$ absorption in the nuclear N1-N2 region. However, the OH absorption is solely confined to the nuclear region and does not display any of the extensions found in this section.

The combined PV diagrams show the existence of five independent H$\alpha$ components found against the nuclear region: (1) a disklike structure with three components with gradients of 1.49 km s$^{-1}$ pc$^{-1}$ south of N1, of 1.15 km s$^{-1}$ pc$^{-1}$ north of N2, and of 0.26 km s$^{-1}$ pc$^{-1}$ between N1 and N2. A single gradient covering the whole range would have a south-north gradient of 0.32 km s$^{-1}$ pc$^{-1}$; (2) the region north of N2 shows a second (reverse) southwest-northeast gradient of 1.0 km s$^{-1}$ pc$^{-1}$; (3) a high-declination east-west structure between 7250 and 7750 km s$^{-1}$ with a gradient of 0.53 km s$^{-1}$ pc$^{-1}$ providing a connection with the NW absorption region; (4) an outflow component reaching 6900 km s$^{-1}$ associated with nucleus N1 with a southwest-northeast gradient of 0.89 km s$^{-1}$ pc$^{-1}$; and (5) some distinct (but marginal) offset
components covering 7000–7750 km s\(^{-1}\) associated with the disturbed region west-southwest of the nucleus N1.

The moment maps. — The first moment H I map in Figure 5 (top) confirms the dominant south-north (component 1) velocity gradient along the N1-N2 axis, suggesting organized rotation. The velocity gradient deduced between N1 and N2 is 0.18 km s\(^{-1}\) per km, which is smaller than the one obtained above from the PV diagrams.

A large-scale east-to-west rotation (component 3) in the northern region causes curved isovelocity lines and continues into the NW region but is interrupted by a lower velocity north-south component crossing the region at W0. This interruption has the signature of the foreground dust lane passing just west of the nuclei in optical images. The dust lane absorption at W0 is at 7400 km s\(^{-1}\), which is close to the systemic velocity of N2.

At the locations of the two nuclei, the systemic velocities in Figure 5 (top) are \(v(N1) = 7235\) km s\(^{-1}\) and \(v(N2) = 7305\) km s\(^{-1}\). The velocity difference of 70 km s\(^{-1}\) is smaller than the 120 km s\(^{-1}\) found in the PV diagrams of Figure 3, which would come closer to the difference of 182 km s\(^{-1}\) found at higher resolution (Beswick et al. 2001) and in other molecular data. Outside the main structure we can also identify absorption at W2 at \(v = 7034\) km s\(^{-1}\) and at the eastern edge of W4 at 7687 km s\(^{-1}\), which needs confirmation.

The second moment map in Figure 5b shows a rather curious structure with a band of large velocity widths (more than 150 km s\(^{-1}\)) running from N1 and N2 into the NW region. For comparison, the MERLIN line widths are largest at N2 with 300 km s\(^{-1}\) and narrowest toward the northwest with 60 km s\(^{-1}\) (Beswick et al. 2001).

A distinct low-velocity component (seen also as 4 and 5 in the PV data) located at west-southwest of N1 is likely related to the superwind outflow. This feature at P.A. = 25° appears to have an east-west velocity gradient and lower line widths. It should be noted that this structure also appears at the same location in the OH data. Furthermore, the position angle of the outflow component also points to the eastern edge of the W4 component that is also found in the moment maps of Figures 5 and 6. In addition, the offset components found at the outflow position in the PV diagrams have a velocity range of 7000–7750 km s\(^{-1}\), indicating a highly disturbed region.

The H I absorption column density. — The absorption column density presented in Figure 6 and in Table 2 is determined using the absorption-line strengths and the associated continuum data at 1420 MHz (Fig. 1, top). The expression for the hydrogen column density used is \(N(H) = 1.823 \times 10^{18} T_S \int \tau(V) dV \text{ cm}^{-2}\), where \(T_S\) is the hydrogen spin temperature, and \(\tau\) is the absorption optical depth. The map shows the highest column density of \(N(H) = 1.28 \times 10^{22} \text{ cm}^{-2}\) at nucleus N1 using a spin temperature of 100 K. The optical depth is largest at N1 with 0.15 (±0.01) and at N2 with 0.11 (±0.01).

The column density map also shows absorption at W0 with 9.42 \times 10^{21} \text{ cm}^{-2}, and at W4 with 7.78 \times 10^{21} \text{ cm}^{-2}. If one assumes that the absorption at W0 is composed of a continuation of the NW absorption plus a contribution of the foreground dust lane at a significantly lower velocity, then the dust lane specific column density is estimated at 3.2 \times 10^{21} \text{ cm}^{-2}. The NW structure at P.A. = 60° is located at some 2 kpc from the nuclei and W0 is at 2.7 kpc. In addition, the NE elongation at P.A. = 45° extends almost 2.0 kpc from N2. The absorption spot W4 is 4.2 kpc away from N1.

3.3. The OH Lines

The OH line characteristics. — The integrated spectrum of the 1667 and 1665 MHz OH absorption is depicted in Figure 7 in the rest frame of the 1667 MHz line. The adopted systemic velocities of the two nuclei of 7258 and 7440 km s\(^{-1}\) lie just below and above the absorption peaks of the two lines. The integrated OH spectrum across the whole source shows an overall line ratio of 1.3 for the two absorbing transitions. Channel maps of the OH data cube have not been displayed because the spectral information is better presented by other means.

The shallowness and irregularity of the single-dish OH absorption spectrum (Baan et al. 1985) suggested that some of the absorption in the system had been filled in with emission. With this in mind, the OH data have been scrutinized in a search for OH emission but no clear evidence has been found. The two absorption
lines in Figure 7 suggest an asymmetry of the line profiles and nonsimilarity that could indeed be explained by a partial infilling with emission on the high-velocity side of the 1665 MHz line and/or at the low side of the 1667 MHz line.

The OH hyperfine ratio in the nuclear absorption region is depicted in Figure 8 using the sums of the channel maps for the 1667 and 1665 MHz lines as depicted in Figure 7. The central region between the nuclei exhibits values below 1.0 and going below 0.8 on the west side. Locations outside the central region have values in the optically thick and optically thin LTE range of 1.0 to 1.8. The values of the hyperfine ratios at N1 and N2 are 1.6 and 1.2, respectively. The occurrence of non-LTE conditions in the velocity range of 7330 km s\(^{-1}\) and below may be explained with emission in the 1667 MHz line. The range around 7300 km s\(^{-1}\) corresponds to a missing (low-velocity) shoulder of the 1667 MHz line profile (see Fig. 7).

The OH PV maps.—The OH data shows substantial absorption only against the nuclear radio double source and no large extensions can be found outside the nuclear area. A single OH velocity-position map is presented at P.A. = 20° along the N1-N2 axis (Fig. 9). Different than that of the H\(\text{I}\) absorption, the bulk of
The OH absorption occurs between the two nuclear sources at 7325 km s\(^{-1}\). The dominant south-north velocity gradient in the central region of 0.19 km s\(^{-1}\) pc\(^{-1}\) is somewhat smaller than that of the central H\(^i\) component. Similar to the H\(^i\) absorption, there is a changing velocity gradient across the region with two separate components with velocity gradients outside N1 and N2. The gradients in the two shoulders in Figure 9 south of N1 and north of N2 are estimated to be 0.75 km s\(^{-1}\) pc\(^{-1}\), which is much steeper than the central part but still lower than that of the H\(^i\) estimate. This component has also a counterpart in the 1665 MHz lines and is related to the connecting bridge between the 1665 and 1667 MHz lines.

In the northern region close to N2, there is a distinct component with an (estimated) opposite west-east velocity gradient of 0.30 km s\(^{-1}\) pc\(^{-1}\). A similar structure has been found in the H\(^i\) data (Fig. 4), which has been associated with rotation due to the northern galaxy along the N2-NW line. In the spectrum of Figure 7 this translates into the low-velocity shoulder of the 1667 MHz line.

### Table 2

| Component                | V\(^{\text{H}i}\)\(^\text{a}\) (km s\(^{-1}\)) | \(\Delta V^{\text{H}i}\) (km s\(^{-1}\)) | \(\tau_{\text{H}i}\) | \(f_{\text{H}i, d1}\) (km s\(^{-1}\)) | \(N_{\text{H}i}^{\text{e}}\) (cm\(^{-2}\)) | \(f_{\text{OH}, d1}\) (km s\(^{-1}\)) | \(\tau_{\text{OH}67}\) | \(\Delta V^{\text{OH}67}\) (km s\(^{-1}\)) | \(N_{\text{OH}67}^{\text{d}}\) (cm\(^{-2}\)) |
|--------------------------|---------------------------------------------|----------------------------------------|------------------------|------------------------------------------|--------------------------------------------|------------------------------------------|------------------------|------------------------------------------|--------------------------------------------|
| Nucleus N1               | 7295                                       | 909                                    | 0.15                   | 70.4 ± 0.7                               | 1.28 (22)                                  | 7243                                      | 295                    | 0.038                                    | 1.39 ± 0.1                               | 6.55 (15)                               |
| Central peak             | 7295                                       | 913                                    | 0.12                   | 70.4 ± 0.7                               | 1.28 (22)                                  | 7274                                      | 406                    | 0.063                                    | 2.29 ± 0.2                               | 1.1 (16)                                |
| Nucleus N2               | 7339                                       | 870                                    | 0.11                   | 55.5 ± 0.5                               | 1.01 (22)                                  | 7363                                      | 406                    | 0.035                                    | 1.28 ± 0.1                               | 6.03 (15)                               |
| NE corner                | 7600                                       | 303                                    | 0.52                   | 25.6 ± 1.5                               | 6.67 (21)                                  | ...                                       | ...                    | ...                                       | ...                                       | ...                                     |
| NW structure             | 7513                                       | 606                                    | 0.07                   | 34.2 ± 1.3                               | 6.23 (21)                                  | ...                                       | ...                    | ...                                       | ...                                       | ...                                     |
| Dust lane                | 7270                                       | 800                                    | 0.05                   | 51.7 ± 1.2                               | 9.42 (21)                                  | ...                                       | ...                    | ...                                       | ...                                       | ...                                     |
| E1 component             | 7530                                       | 380                                    | 0.04                   | 46.8 ± 1.3                               | 8.55 (21)                                  | ...                                       | ...                    | ...                                       | ...                                       | ...                                     |
| W2 component             | 7034                                       | 217                                    | 0.04                   | 21.4 ± 1.5                               | 3.90 (21)                                  | ...                                       | ...                    | ...                                       | ...                                       | ...                                     |
| W4 component             | 7687                                       | 390                                    | 0.07                   | 42.7 ± 1.3                               | 7.80 (21)                                  | ...                                       | ...                    | ...                                       | ...                                       | ...                                     |

\(^{a}\) Peak values.

\(^{b}\) Full-width zero-intensity values.

\(^{c}\) Assumed \(T_S = 100\) K for H\(^i\).

\(^{d}\) Assumed \(T_{\text{ex}} = 20\) K for OH.

The moment maps.—The first moment map of the 1667 MHz line in Figure 10 (bottom) shows a smooth velocity gradient, that resembles and confirms the H\(^i\) characteristics in the central region. The velocity gradient starts in the SE region close to N1 as part of the southern galaxy and continues via N2 into the northeast.

![Fig. 7.—Integrated spectrum of OH absorption taken across both nuclei with the 1667 MHz (left) and the 1665 MHz (right at +351 km s\(^{-1}\)). The velocity axis of the spectrum is in the rest frame of the 1667 MHz line.](image)

![Fig. 8.—Hyperfine line ratio of the 1667 and 1665 MHz absorption lines across the nuclear region. The locations of the two nuclei are indicated in the diagram. The contour levels are 0.8 – 1.8 with intervals of 0.2. The lowest contour of 0.8 is at the west side of the central region and subsequent contours are increasingly further out toward the two nuclei. Values of 1.6 are found at N1 and 1.2 at N2. The highest optically thin ratio of 1.8 is found north of N1, while south of N1 the ratio decreases again to 1.4.](image)
direction. There is some evidence of a superposed east-northwest gradient starting at N2 that is associated with the northern galaxy. The velocities derived for N1 and N2 from the second moment map are 7255 and 7370 km s\(^{-1}\).

The line width in the 1667 MHz line displayed in Figure 10 (top) is largest at a location between the two nuclei similar to the \(\text{H} \text{i}\) case, but with a value of 80+ km s\(^{-1}\) it is significantly smaller than the 150+ km s\(^{-1}\) width found in \(\text{H} \text{i}\). It should be noted that the highest line widths coincide partially with the region of non-LTE (super optically thin with ratio \(\leq 1.0\)) excitation in Figure 8. The moment maps of the 1665 MHz lines are all consistent with those of the 1667 MHz.

Figure 10 also displays the curious structure southwest of N1 at P.A. = -25° that is also present in the \(\text{H} \text{i}\) data, and represents the direction of a jet or is part of a wider nuclear outflow. At that location the velocity field is confused and the \(\text{OH}\) line widths become narrower. Further to the west there is an additional (disjoint) region with very low 20 km s\(^{-1}\) line width at 7360 km s\(^{-1}\), which may relate to the (streaked) extensions at low declination (57.0°) in the PV diagram (Fig. 9).

The \(\text{OH}\) column density.—The \(\text{OH}\) column density has been presented in Figure 11 and has been based on the 1667 MHz optical depth using the 18 cm continuum map (Fig. 1) and the expression 
\[ N_{\text{OH}67} = 2.35 \times 10^{18} T_{\text{ex}} \int \tau(V) \, dV, \]
where the excitation temperature \(T_{\text{ex}}\) has a typical value of 20 K. The region with the highest \(\text{OH}\) column density of \(N_{\text{OH}67} = 1.08 \times 10^{16} \text{ cm}^{-2}\) occurs halfway between N1 and N2. The column densities at N1 and N2 are a factor of about 1.8 lower. The peak \(\text{OH}\) optical depth of 0.063 is a factor of 2 smaller than that of \(\text{H} \text{i}\).

4. DISCUSSION

4.1. The Central Gas Concentration

The central gas concentration is clearly present in the \(\text{OH}\) data, where it peaks between the nuclei at about 0.9° north of N1 (and closer to N2), and also in the \(\text{H} \text{i}\) data, where the peak occurs close to N1. In a projection scenario with N1 being located behind N2 (see next section), the largest column densities should occur at N1 and gas distributions of the two galaxies are displaced by only 790 pc. Therefore, the column differences between the absorption peaks and the nuclei of 1.3 for \(\text{H} \text{i}\) and 1.8 for \(\text{OH}\) could be accommodated by a superposition of two galactic gas distributions. However, the velocity gradient in the central region of
The centrally peaked OH absorption shows rough agreement with the findings for other thermally excited molecules such as \( \text{CO} \) and \( \text{H}_2 \) emissions (van der Werf et al. 1993; Ohyama et al. 2000; Tacconi et al. 1999). The \( \text{HI} \) absorbing gas samples a larger volume than the molecular gas, and different structural components may contribute to the \( \text{HI} \) and molecular absorption component. However, the central OH and \( \text{HI} \) velocity gradients of about 0.25 km s\(^{-1}\) pc\(^{-1}\) are surprisingly different from the velocity gradient of the \( \text{CO} J = 2-1 \) emission of 0.74 km s\(^{-1}\) pc\(^{-1}\). Possibly the CO data also samples the higher gradients of the gas in the two disks.

The distinct radio continuum region designated N3 is not necessarily a third nucleus, but is rather an area of enhanced (super-)star formation region in the interaction zone of the two galaxies and is currently embedded in the extended radio structure in the north.

4.3. The Dynamics of NGC 6240

The nuclei N1 and N2 are separated by 1.575\(^\circ\) corresponding to 793 pc. If the interacting galaxies were in the plane of the sky, they would be at very different velocities and their nuclear regions would be coalesced and extremely confused. Since we see apparently distinct nuclear entities, they are more distant from each other and have only a projected distance of 793 pc. Considering that the highest \( \text{HI} \) and molecular column densities lie in between the nuclei and that the X-ray source in N1 shows the highest column density, it is most plausible that N1 lies behind N2. The small velocity difference suggests that the N1-N2 connecting axis has a small angle with the line of sight and the relative values of the velocities at N1 and N2 suggest that the galaxies are just past transit.

The \( \text{HI}/\text{OH} \) systemic velocities at the nuclei can be used for a dynamical/orbital scenario for the nuclei projected on the sky.
Given the relatively large beam, we find \( \text{H}\alpha \) estimates of 7235 and 7305 km s\(^{-1}\) and \( \text{OH} \) estimates of 7255 and 7370 km s\(^{-1}\), which are nominally consistent with the higher resolution \( \text{H}\alpha \) values of 7258 and 7440 km s\(^{-1}\) (Beswick et al. 2001). These values are larger than the difference of stellar velocities of 50 km s\(^{-1}\) (Tecza et al. 2000), but consistent with the \( \text{H}_2 \) (\( \simeq 150 \) km s\(^{-1}\)), \( \text{CO}(2-1) \) (\( \simeq 100 \) km s\(^{-1}\)), and Bracket \( \gamma \) emission data (Lira et al. 2002; Ohyama et al. 2000; Tecza et al. 2000). We adopt the high-resolution \( \text{H}\alpha \) estimate of the velocity difference for the nuclei \( \delta V = 182 \) km s\(^{-1}\).

As an attempt at the dynamics of the close encounter, we assume a simple \textit{edge-on circular orbit for two equal masses} \textit{M} around the center of mass, and a (small) projection angle \( \theta \) between our line of sight and the connecting line between the two nuclei. The description of the orbital motion of the system follows from: \( \sin (\theta) = 0.031 V^2 G^{-1} M_n^{-1} D_{\text{obs}} \), where \( M_n \) is the combined dynamic mass of the nuclear region, and \( D_{\text{obs}} \) is the projected distance between the nuclei. The estimate of Tecza et al. (2000) of the stellar mass in each of the nuclei of about \( 2 \times 10^5 \) \( M_\odot \) gives a combined dynamic mass of the nuclei of \( M_n = 1.2 \times 10^{10} \) \( M_\odot \), using the smaller velocity difference. The central gas concentration also constitutes a significant fraction of the dynamic mass, such that \( M_{\text{gas}} (R \leq 470 \) pc) \( \approx (2-4) \times 10^9 \) \( M_\odot \). Similar to the previous work (Tacconi et al. 1999). For this reason, we adopt a dynamic mass for the nuclei of \( M_n = 1.5 \times 10^{10} \) \( M_\odot \), which results in \( \theta = 13.4^\circ \) (projection factor = 4.3), an orbital velocity of 392 km s\(^{-1}\), and a distance between the nuclei of 3.42 kpc. The orbital period is about 27 Myr. This scenario gives a sufficiently large separation distance to ensure identifiable nuclear/gas characteristics at this well-advanced stage just before coalescence.

\subsection*{4.4. The Two Interacting Galaxies}

The \( \text{OH} \) and \( \text{H}\alpha \) velocity field of the nuclear region is dominated by the large-scale organized motion of the accumulated gas structure. However, the detailed velocity pattern displayed in Figures 5 (top) and 10 (top) suggest the presence of large-scale velocity components associated with the interaction of the two galaxies. The analysis of the stellar velocity field in the southern galaxy suggests a northwest-southeast rotation (\( \iota = 60^\circ \)) at \( \text{P.A.} = -34^\circ \) with \( V_{\text{rot}} = 270 \pm 90 \) km s\(^{-1}\) (Tecza et al. 2000). The northern galaxy (\( \iota = 33^\circ \)) displays a southwest-northeast rotation at \( \text{P.A.} = 41^\circ \) with \( V_{\text{rot}} = 360 \pm 195 \) km s\(^{-1}\).

The \( \text{H}\alpha \) and \( \text{OH} \) absorption in the northeast extension (Figs. 5 and 10, top panels) suggests a southwest-northeast rotation for the northern galaxy at \( \text{P.A.} = 40^\circ -50^\circ \) with an \( \text{H}\alpha \) gradient of 1.15 (or 0.75 for \( \text{OH} \)) km s\(^{-1}\) pc\(^{-1}\) north of N2, which is consistent with a stellar gradient of 1.2 km s\(^{-1}\) pc\(^{-1}\). However, the region south of N1 also shows evidence of a south-north rotation at 1.49 km s\(^{-1}\) pc\(^{-1}\) for \( \text{H}\alpha \) and 0.75 km s\(^{-1}\) pc\(^{-1}\) for \( \text{OH} \), and is associated with the large gas structure of the interaction. In addition, there is a weak low-velocity \( \text{H}\alpha \) signature south of N1 down to 6900 km s\(^{-1}\) with the southwest-northeast gradient of 0.89 km s\(^{-1}\) pc\(^{-1}\), which might constitute the motion of the southern galaxy. The absence of a clear velocity signature of the southern galaxy could easily result from the column density around N1. Furthermore, the region west-southwest of N1 is very perturbed by the outflow and shows evidence of components with velocities up to 7750 km s\(^{-1}\).

\subsection*{4.5. The Superwind Outflow}

The continuum structure extends from N1 and N2 in all directions, including to the northwest region and the radio arc. The western radio arc results from the shocked regions forming the boundaries of a symmetric superwind-driven outflow emanating from N1 (see Heckman et al. 1990), that is less prominent toward the east. In addition, there is a considerable extended radio emission resulting from distributed star formation in the southwest and northeast regions. Besides the presence of two AGNs, the radio properties of the nuclear region suggest dominant starburst activity (Beswick et al. 2001; Gallimore & Beswick 2004). The \( K \)-band emission at both nuclei suggests dominant populations of red supergiants (Tecza et al. 2000). Recent X-ray data also suggest that the outflow is indeed symmetric and that there are outflow remnants on both sides of the nuclei.

The \( \text{H}\alpha \) data shows a blueshifted component along the line of sight extending to \(-300 \) km s\(^{-1}\) with respect to N1 (Fig. 4). Similarly there is a low-velocity component in the \( \text{OH} \) data at \(-120 \) km s\(^{-1}\) (Fig. 9), which produces a wing on the 1667 MHz line (Fig. 7). Ohyama et al. (2000) note a \(-250 \) km s\(^{-1}\) component in the \( \text{H}_2 \) emission. These blueshifted features could represent line-of-sight outflows and shocks, which are driven into the denser nuclear interstellar medium by the nuclear starburst and are associated with the superwind.

The \( \text{H}\alpha \) and \( \text{OH} \) velocity and line width data west-southwest of N1 as well as the blueshifted \( \text{H}\alpha \) components at N1 clearly confirm that N1 is the origin of the outflows. The lifetime of the starburst has been estimated at \( \approx 10 \) Myr (Tecza et al. 2000), which is about 40\% of the orbital period of 27 Myr derived above. The orbital motion may thus have resulted in smearing out the X-ray and radio emission regions. In addition, the difference of the emission strength of the northern and southern parts of the radio arc may also have resulted from the “piling up” of emission in the forward direction, which confirms that N1 is moving north. The complicated \( \text{OH} \) and \( \text{H}\alpha \) structures southwest of N1 are associated with the outflow into the western cavity and cover a large velocity range with a mean of about 100 km s\(^{-1}\) below that of the systemic velocity of N1. There is (marginal) evidence of \( \text{H}\beta \) absorption components west-southwest of N1 reaching an extreme of 7750 km s\(^{-1}\). Our \( \text{H}\alpha \) data also displays continuous absorption against the base of the northern radio arc and against arc components W0, W2, and W4.

\subsection*{4.6. The Extended Absorption}

The \( \text{H}\alpha \) absorption is found across much of the extended radio emission, while the \( \text{OH} \) is found only in the central region of the source. The \( \text{H}\alpha \) absorption shows complicated structures with a wide range of velocities and line widths, and relatively low column densities. Some of this material is associated with foreground dust lanes and ejected gas resulting from the interaction.

The extended radio emission in NGC 6240 is associated with the remnants of the two galaxies and the radio arcs resulting from the symmetric superwind outflows emanating from N1 and possibly N2. As discussed above, we find significant absorption and an \( \text{H}\alpha \) velocity gradient of 1.0 km s\(^{-1}\) pc\(^{-1}\) in the NE region, which is associated with the remnant of the northern galaxy. In addition, there is an east-west gradient toward the NW region (at \( \text{P.A.} = -50^\circ \)), where we find the highest \( \text{H}\alpha \) velocities in the system.

The column density map of Figure 6 displays widespread \( \text{H}\alpha \) absorption in the large-scale structure of NGC 6240. Discrete absorption components with column densities in the range of \((0.4-1.0) \times 10^{22} \) cm\(^{-2}\) are found at the continuum component in the NW region and at the W0, W2, and W4 components of the arc structure. The velocities at these components, which are not associated with distinct components in the optical and \( \text{H}\alpha \), suggest an increasing velocity toward the south.

The dominant absorption at W0 is caused by a north-south dust lane passing in the foreground of the continuum structure with an
estimated column density of \(3.2 \times 10^{22}\) cm\(^{-2}\). Images with various optical and X-ray instruments (Max et al. 2005; Komossa et al. 2003) show the clear presence of this north-south dust lane that crosses the NW radio structure at W0 and accounts for an added column density. While the distributed H\(\text{i}\) in the NW region has a velocity of about 7500 km s\(^{-1}\), the dust lane has a systemic velocity of about 7270 km s\(^{-1}\), which is close to that of N1. Furthermore, it has no clear velocity gradient because of its distance from the nuclei.

The radio continuum and X-ray images also display two extended structures S and SW of nucleus N1 (see Fig. 1, bottom; Komossa et al. 2003). It is found that a dust-lane structure toward the south divides these two structures. Only weak absorption has been seen against the continuum in this southern region.

4.7. The OH and H\(_2\)O Emission

A narrow H\(_2\)O maser line has been detected toward the nuclear region of NGC 6240 at \(v_{\text{lsr}} = 7565\) km s\(^{-1}\) located within 3 pc from the continuum peak at N1 (Hagiyara et al. 2003). The occurrence of an H\(_2\)O maser is rather unusual in a FIR-dominated galaxy such as NGC 6240, which is more likely an OH Megasmer candidate. OH-MM UGC 05101 also hosts a weak H\(_2\)O maser toward the nuclear region (Zhang et al. 2006). The maser in NGC 6240 is redshifted about 300 km s\(^{-1}\) relative to the systemic velocity of N1, while high-velocity OH or H\(\text{i}\) gas has only been found in the northern region of the source (Figs. 3, 4, and 9). An association of the maser with the AGN could exist with shocked outflows, or jet–molecular cloud interactions, in order to account for these discrepant velocities. Examples of other redshifted jet-related masers can be found in the elliptical NGC 1052 (100–180 km s\(^{-1}\); Claussen et al. 1998) and Mrk 348 (130 km s\(^{-1}\); Peck et al. 2003). Alternatively, there could be either an association with infalling foreground gas to the nuclear region or with an active nucleus.

The shallow and multicomponent Arecibo spectrum of OH in NGC 6240 has been interpreted on the basis of partial infilling of the absorption by emission (Baan et al. 1985). The asymmetries in the spectrum of Figure 7 and the PV diagram Figure 9 could indeed support this notion. While asymmetries suggest emission infilling at the velocity of N2, there is no evidence in the data for this. The bulk of the OH absorption shows an LTE line ratio. Only the western side of the central absorption shows non-LTE ratios that suggest infilling of the 1667 MHz line with emission at the velocity of N1. Non-LTE conditions could be caused by the FIR radiation field, which is dominant in NGC 6240 and has the right infrared colors for FIR pumping as in OH megamasers (Baan 1989; Henkel & Wilson 1990). While there would be enough background radio continuum for this purpose in the N1 system, there is no discernible line emission.

5. SUMMARY

The extended H\(\text{i}\) and OH absorption against the continuum structure has revealed more of the dynamic and evolutionary properties of the interacting system NGC 6240, and complementary evidence obtained at other wavelengths. The radio continuum structure and the associated absorption structure of NGC 6240 is in part the result of a superposition of the two galaxies and their constituents. In a simple dynamic model using H\(\text{i}\) systemic velocities, the northern galaxy with nucleus N2 would be located in front of the southern galaxy with nucleus N1, such that the N1-N2 connecting line would be foreshortened by a factor of 4.3. In this picture N1 would be expected to have the largest absorbing column density, while the central disks of the galaxies would be superposed between the two nuclei.

The radio continuum structure of 15″ × 17″ (7.6 × 8.6 kpc) peaks at the two nuclei of the interacting galaxies with hybrid starburst and AGN emission, and is surrounded by an extended structure associated with star formation activity triggered by the interaction. A large-scale but incomplete loop structure on the western side of the source has been associated with a nuclear blowout and outflow from nucleus N1 of the southern galaxy, while traces of a similar structure can also be found at the eastern side of the source.

The H\(\text{i}\) absorption covers a contiguous 5″ × 8″ (2.7 × 4.2 kpc) region of the continuum structure and provides a large-scale view of the velocity field across this area. The peak of the H\(\text{i}\) absorption falls close to nucleus N1 in such a way that the H\(\text{i}\) column density at N1 is 1.26 times that of N2, and is in agreement with the estimates from X-ray observations.

OH absorption has been found only against the nuclear continuum and extends 2.5″ × 2.0″ (1.25 × 1.0 kpc). The largest column density of the OH absorption falls north of N1 and about halfway between N1 and N2, a fact that agrees with maps of other molecular emissions. The column densities at N1 and N2 are about 60% of that of the central gas structure.

The H\(\text{i}\) and OH velocity fields reveal parts of the velocity gradients of the two individual galaxies buried in the central region. Velocity gradients at various locations suggest gas motions resulting from the interaction of the two galaxies. In particular, the location of N1 and the region to the west displays blueshifted (line-of-sight) outflow components, as well as structural components related to the sideways outflow into the western bubble. This evidence clearly confirms the nuclear activity at N1 as the origin of the outflows and the cause of the radio arc, which is consistent with the evidence from X-ray and H\(\alpha\) data.

Distinct velocity components are found in the northern region and along the radio structure northwest of the nuclei. A foreground dust lane passes across the northwest radio loop structure. Absorption in more distant continuum components do not reveal a coherent velocity pattern. The large width of the H\(\text{i}\) absorption line across the central part of the source confirms the violent dynamics of the system. The highest OH velocity widths are found at the central gas deposit, but they are significantly lower than those of H\(\text{i}\) and therefore less affected by the merger dynamics.

The central gas structure may result from a superposition of the disks of the two galaxies. There may also be accumulation of gas in the center of mass of the dynamic system. The central gas accumulation between the nuclei behaves as an independent structure with a velocity gradient proportional to the velocity difference of the two nuclei, and the gas appears locked into the motion of the system. The H\(\text{i}\) and OH velocity gradients for the central region are much smaller than that of CO(2−1), which may suggest that different observations detect distinctly different scale sizes within these structures.

The OH hyperfine ratio in the absorption region suggests mostly LTE conditions across the nuclear region, except in the western part of the central gas accumulation where non-LTE conditions are found. Non-LTE conditions may suggest that radiative far-infrared pumping actively reduces the absorption on the low-velocity side of the 1667 MHz OH line. No further OH maser emission has been found in the system.

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