Superwind-Driven Intense H\textsubscript{2} Emission in NGC 6240

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We have performed a long-slit K band spectroscopic observation of the luminous infrared galaxy NGC 6240. Spatially extended H\textsubscript{2} emission is detected over 3.3 kpc around the two nuclei. The peak position of the H\textsubscript{2} emission is located at 0.−2pt"3−0.−2pt"4 km s\textsuperscript{-1} with respect to V\textsubscript{sys} which is recognized as a distinct C-shape distortion in the velocity field around the southern nucleus, the high-velocity blueshifted “wing” component (−1000 km s\textsuperscript{-1}) emission can be interpreted as a pure thermal excitation.


Introduction

NGC 6240 (= IRAS 16504+0228 = UGC 10592 = IC 4625) is one of the famous luminous infrared galaxies (LIGs: L(\textsubscript{IR})= L(8 − 1000\textsubscript{\mu}m)= 4.6 \times 10\textsuperscript{11}; Sanders & Mirabel 1996) at a distance of 98 Mpc (Heckman et al. 1987). It is a merging system containing two radio and near-infrared nuclei (Condon et al. 1982; Fried & Schulz 1983; Eales et al. 1990; Thronson et al. 1990; Herbst et al. 1990; Colbert, Wilson, & Bland-Hawthorn 1994; Sugai et al. 1997; Tacconi et al. 1999). Although this galaxy is often called as a prototypical LIG (Wright, Joseph, & Meikle 1984; Joseph & Wright 1984; Heckman, Armus, & Miley 1987, 1990; Armus, Heckman, & Miley 1990; Klaas et al. 1997), it is also well known as an object with unusually luminous near-infrared molecular hydrogen (H\textsubscript{2}) emission (e.g., Rieke et al. 1985; DePoy, Becklin, & Wynn-Williams 1986). Several H\textsubscript{2} excitation mechanisms have been proposed to date including 1) thermal excitation driven by shocks (Rieke et al. 1985; DePoy et al. 1986; Lester, Harvey, & Carr 1988; Elston & Maloney 1990; Herbst et al. 1990; van der Werf et al. 1993; Sugai et al. 1997), 2) UV fluorescence (Tanaka, Hasegawa, & Gatley 1991), 3) soft X-ray heating (Draine & Woods 1990; see also Mouriri et al. 1989), and 4) formation pumping (Mouri & Taniguchi 1995). Recently, Sugai et al. (1997) presented their new high-quality spectrum and clearly showed that the H\textsubscript{2} spectrum can be interpreted as a pure thermal excitation.
Although the origin of the H$_2$ emission in LIs and ultraluminous infrared galaxies (ULIs: Sanders & Mirabel 1996) is generally attributed to their intense star-formation activities at their nuclei and/or active galactic nuclei (AGNs) (e.g., Moorwood & Oliva 1990; Goldader et al. 1995), NGC 6240 is often considered to be an exceptional case. It is often discussed that the global shock caused by a galaxy-galaxy collision brings its huge H$_2$ luminosity. This is because 1) current star-formation activity (or, current supernova explosion rate) is not intense enough to reproduce its huge H$_2$ luminosity (e.g., Rieke et al. 1985; Draine & Woods 1993), 2) unusually large intensity ratio of H$_2$ $v = 1 - 0$ $S(1)$ [hereafter, $1 - 0$ $S(1)$] to Br$_{\gamma}$ ($\approx 45$: van der Werf et al. 1990) cannot be explained by normal star-formation activities (e.g., Rieke et al. 1985; Draine & Woods 1993), and 3) the peak position of the H$_2$ emission is located not at each nucleus but between the two nuclei where no star-forming activity is detected (Herbst et al. 1990; van der Werf et al. 1993; Sugai et al. 1997). However, it is important to remember that these kinds of evidence are not direct ones, i.e., we do not have any spatial and kinematic information directly suggesting that the intense H$_2$ emission does come from the galaxy-galaxy collision interface.

Although thermal excitation driven by the galaxy-galaxy collision might be a main excitation mechanism of the strong H$_2$ emission, there remains some possibilities of other excitation mechanisms. Like other normal LIs, it seems very likely that intense starburst activity and/or AGN also contribute more or less to the H$_2$ emission. In fact, there are many pieces of evidence suggesting intense starburst activity in this galaxy (Wright et al. 1984; Rieke et al. 1985; Smith, Aitken & Roche 1989; van der Werf et al. 1993). Also there are many pieces of evidence suggesting an activity of “superwind”, which is a galaxy scale blastwave driven by numerous supernova explosions (Tomisaka & Ikeuchi 1989; Heckman et al. 1990; Suchkov et al. 1994), and some previous authors have indeed suggested its importance to the H$_2$ emission (Elston & Maloney 1990; Herbst et al. 1990; van der Werf et al. 1993). X-ray heating from an AGN, which is recently found by the hard X-ray observation (Iwasawa & Comastri 1998), might also contribute to the H$_2$ emission (Mouri et al. 1989). In this way, the physical mechanism of the H$_2$ emission seems to be very complicated in this galaxy.

In order to study the origin of the H$_2$ emission in more detail and to understand the nature of the activity of NGC 6240, it is important to obtain a spatial information of the emission-line properties. Thus, we have conducted a long-slit K-band spectroscopic observations of this galaxy with Subaru 8.2m telescope (Kaifu 1998) in order to perform detailed spectroscopic analyses.

Observation and Data Reduction

Observations were performed on the night of 1999 April 29 during the test observation phase of Subaru telescope at the top of Mauna Kea, Hawaii, using the grism spectroscopy mode of CISCO (Cooled Infrared Spectrograph and Camera for OHS: Motohara et al. 1998). The detector used is a 1024 $\times$ 1024 Hawaii array with a projected pixel size of 0.2pt$^\prime$115 along the slit and 8.6Å at 2.3$\mu$m along the dispersion direction. Slit width is 0.2pt$^\prime$5 and slit length is about 2 arcminutes, which is long enough to obtain sky background information in each on-source frame. The slit position angle was set to the position angle of the two nuclei (19$^\circ$: Herbst et al. 1990; Thronson et al. 1990) in order to observe the northern and southern nuclei (hereafter, the N nucleus and the S nucleus, respectively) as well as the intergalactic region at a same time (Figure 1. This image was obtained with the CISCO imaging mode with a K band filter through a wide 2$\prime$/slit with the position angle of 19$^\circ$. Note that because this image was taken just for the source acquisition, the dark subtraction and the flatfielding were not applied. It is presented just for the reader to easily understand the rough source positions along the slit. The image is averaged over 2 pixels (0.2pt$^\prime$23),.

The total exposure time was 1500 second for on source (fifteen exposures, each of 100 second integration). The object was placed on only two positions along the slit during exposures. A nearby A3-type star SAO 122007 and a K0-type star SAO 122106 were also observed just before observing NGC 6240 in order to correct for atmospheric absorption. Seeing size around K band wavelength were 0.2pt$^\prime$5 $-$ 0.2pt$^\prime$6 during the observations. Dome flat spectra were obtained at another observing run on 1999 June 25 with the same instrumental setup.

Data reduction was performed with IRAF. IRAF is distributed by the National Optical Astronomy Observatories, which are operated by the Association of Universities for Research in Astronomy, Inc., under cooperative agreement with the National Science Foundation. First, the dark is subtracted from each frame. Each dark-subtracted frame was divided by the dark-subtracted dome flat spectrum. Then, wavelength
calibration of each frame was made using the telluric OH emission lines to an accuracy of $\sim 2.6\AA$. The spectral resolution measured from the OH emission lines was $\sim 26\AA$ FWHM at $2.2\mu m$ ($350$ km s$^{-1}$). We have measured the wavelength of the OH lines in the wavelength-calibrated sky spectra and found that the systematic error is less than $1\AA$ around $2.2\mu m$ ($14$ km s$^{-1}$). Background sky emission was removed by interpolating the adjacent sky spectra with a linear interpolation. The wavelength calibrated frames were combined using $3\sigma$ clipping averaging method after shifting the images along the slit. The spectra of the standard stars were also reduced in the same way. Br$\gamma$ absorption feature of the A-type star was removed in the following way. First, the spectrum of the A-type star was divided by that of the K-type star in order to cancel out the common features such as the atmospheric absorption and the instrumental sensitivity. The resultant ratio spectrum shows an isolated Br$\gamma$ absorption feature and this feature was removed using Voigt profile fitting. Then, the ratio spectrum was multiplied by the spectrum of the K-type stars, giving modified A-type star spectrum without Br$\gamma$ absorption feature. The modified spectrum was used for correcting the atmospheric absorption features and instrumental sensitivity assuming a 8590 K blackbody spectrum. Because the sky condition was not photometric during the observations, no absolute flux calibration was made.

Results

Broadband image

Broad K band image (Figure 1) clearly shows two nuclei (the N and the S nuclei) at a separation of $\sim 1.2pt''9$ with the position angle of $\sim 19^\circ$. This result is consistent with the previous studies in K band (Eales et al. 1990; Herbst et al. 1990; Thronson et al. 1990; Sugai et al. 1997), although Herbst et al. (1990) reported a slightly smaller separation of the two nuclei ($1.2pt''52 \pm 0.2pt''02$).

One must be careful when comparing the nuclear positions seen in the radio continuum and the K band image. Colbert et al. (1994) and Tacconi et al. (1999) found the double nuclei in the radio continuum emission. Although the position angles of the two radio nuclei ($19^\circ - 4.5pt..5pt7$ and $21^\circ$ at 8.3 GHz and 5 GHz, respectively) are consistent with one of the K band nuclei ($19^\circ$), the distance between the two is significantly smaller in radio ($\sim 1.2pt''53$ and $1.2pt''7$ at 8.3 GHz and 5 GHz, respectively) than in K band ($\sim 1.2pt''9$). This apparent discrepancy can be understood as an effect of the dust extinction. The visual extinction ($A_v$) of this galaxy inferred from the large column density ($N_{H_2}2 \times 10^{23}$ cm$^{-2}$) is as large as 200 mag (Tacconi et al. 1999), indicating heavy dust extinction even at K band ($A_K \sim 0.112 \times A_v22$ mag; Binney & Merrifield 1998). Thus the true nuclei should be at the extinction-free radio nuclei, i.e., the true N and S nuclei are located at slightly south and north of the apparent K band positions ($\sim 0.2pt''1 - 0.2pt''2$), respectively.

The spectra and the flux distribution

Spatially extended H$_2$ emission is detected over $7''$ region (3.3 kpc) around the two nuclei. Figure 2 shows the K band spectra of NGC 6240 at various positions. Rich H$_2$ line features including $1-0$ $S(0)$, $1-0$ $S(1)$, $1-0$ $S(2)$, $1-0$ $S(3)$, $2-1$ $S(1)$, and $2-1$ $S(3)$ emission lines are detected at most positions. The $2-1$ $S(2)$ and possibly $2-1$ $S(4)$ lines are also detected at some positions. Weak Br$\gamma$ emission is detected at both the N and the S nuclei. Deep stellar CO absorption is also detected at both nuclei, being consistent with the report by Lester & Gaffney (1994).

The peak position of $1-0$ $S(1)$ is located at about $0.2pt''3 - 0.2pt''4$ north-north-east of the S nucleus (Figure 3) and is much closer to the S nucleus than to the N nucleus. Recent high resolution $^{12}$CO($J=2-1$) mapping shows that the CO peak position is located at $0.2pt''6$ north-north-east of the S nucleus seen in the radio continuum images (Tacconi et al. 1999) and is marked in Figure 1. Thus, the peak position of $1-0$ $S(1)$ is located almost at the midpoint between the CO peak position and the S nucleus. This result is inconsistent with the previous works based on narrow-band emission-line imagings, showing that intense $1-0$ $S(1)$ emission arises from between two nuclei with its peak around the midpoint of the two (Herbst et al. 1990; van der Werf et al. 1993; Sugai et al. 1997). Note, however, that the overall spatial extent of the H$_2$ emission found in our data is nearly consistent with the previous results. The equivalent width of the $1-0$ $S(1)$ emission is the lowest (20 - 40A) at both nuclei, where the continuum emission is the strongest, and is larger at other regions (100A).

The velocity field

The heliocentric velocities and the line widths of the $1-0$ $S(1)$ emission measured with a single Gaussian fitting at various positions are shown in Figure 3. A continuum-subtracted peak-normalized $1-0$ $S(1)$
spectroscopic image is also shown in Figure 4. The velocity is nearly constant and is approximately 7300 km s\(^{-1}\) in the northern region including the N nucleus and its north. We find the systemic velocity \(V_{\text{sys}}\) of NGC 6240 \(\approx 7300\) km s\(^{-1}\) from compilation of the previously published infrared and radio observations (the previous measurements of \(V_{\text{sys}}\) are summarized in Table 1). Thus, the radial velocity of the \(H_2\) emitting gas coincides with the systemic one and the gas motion is relatively quiescent in the northern region.

On the other hand, we find a remarkable velocity variation in the southern region: the emission line is significantly blueshifted and the velocity field is highly disturbed to form a C-shaped distortion over \(\approx 1''\) (450 pc) region around the S nucleus (see Figure 4). At \(-0.2\pi/3 - 0.2\pi/5\) south from the S nucleus the velocity reaches down to \(-250\) km s\(^{-1}\) \((V_{\pi}, 7050\) km s\(^{-1}\); see Figure 3) with respect to \(V_{\text{sys}}\). It must be remembered that the true position of the S nucleus after correcting for the extinction between the two nuclei is expected to be located about \(-0.2\pi/3 - 0.2\pi/2\) north of the apparent K band nucleus. Thus, the center of the C-shaped distortion almost corresponds spatially to the true S nuclear position. It is noteworthy that about 50\% of the \(1 - 0\) \(S(1)\) emission covered in our slit comes from this blueshifted region. This kind of a peculiar velocity field has been previously found by Elston & Maloney (1990), but they could not resolve the detailed structure of the velocity field because of the limited spatial and velocity resolution of their spectrum. We first revealed the detailed dynamical structure of the circumnuclear \(H_2\) emission-line region of NGC 6240.

This remarkable C-shaped velocity field would account for the difference between the flux peak position of \(1 - 0\) \(S(1)\) measured by this work and that derived from the previous narrow band imagings. As pointed out in the previous section, we find that the peak position of \(1 - 0\) \(S(1)\) is located much closer to the S nucleus than previously reported positions. How can we understand this difference? Using narrow band imagings, Sugai et al. (1997) showed that the peak of \(1 - 0\) \(S(1)\) is located between the two nuclei. Their images were taken with three Fabry-Perot settings at \(V_{\text{sys}}\) \((7339\) km s\(^{-1}\) in their paper), \(V_{\text{sys}} + 175\) km s\(^{-1}\), and \(V_{\text{sys}} - 175\) km s\(^{-1}\). Comparing with our results, it seems likely that the most blueshifted \(1 - 0\) \(S(1)\) emission \((\approx 7000 - 7100\) km s\(^{-1}\)) could not be detected in their images. Based on their three narrow-band images (centered at \(V_{\pi}=6910, 7390,\) and \(7470\) km s\(^{-1}\)), van der Werf et al. (1993) showed that the position of the \(1 - 0\) \(S(1)\) peak moves from south to north with increasing velocity, although the peak position of the velocity-integrated \(1 - 0\) \(S(1)\) emission comes around the midpoint of the two nuclei. The blueshifted \(1 - 0\) \(S(1)\) emission found in our data \((V_{\text{sys}} - 250\) km s\(^{-1}\)) should be detected in their blue-band image in which the peak is closer to the S nucleus, being consistent with our result. Herbst et al. (1990) found a southwest extension of the \(1 - 0\) \(S(1)\) emission \((-0.2\pi/5\) from the S nucleus) in addition to the component around the midpoint of the two nuclei. Although Sugai et al. (1997) emphasized that the peak position of the \(1 - 0\) \(S(1)\) emission is located between the two nuclei, we point out that their contour plot also shows an extension toward the southwest direction (see their Figure 1). This extension seems to correspond to the southwest extension found in Herbst et al. (1990). Since our slit position angle is \(19^\circ\), it seems likely that our slit covers a part of this extension. If this component is blueshifted with respect to \(V_{\text{sys}}\), then it would be observed as a blueshifted component around the S nucleus in our data. In these ways, we find that our result is consistent with the previous results.

In addition to the blueshifted emission around the S nucleus, we find a high-velocity blueshifted emission-line “wing” whose velocity exceeds \(-1000\) km s\(^{-1}\) with respect to the peak velocity of the profile (Figure 4). This kind of a profile was previously found by van der Werf et al. (1993). With our spatially resolved spectra, we can investigate the spatial distribution of this high-velocity wing component and find that such a component extends around the S nucleus and to its southern regions \((\approx 2'', \sim 950\) pc). The line width is nearly constant at the region between the two nuclei and around the N nucleus \((550 - 600\) km s\(^{-1}\) FWHM after correcting for the instrumental line broadening), which is consistent with the previous results (e.g., van der Werf et al. 1993). It is well known that this galaxy shows unusually broader line width \((\approx 550\) km s\(^{-1}\)) compared with other galaxies with the intense \(H_2\) emission (e.g., van der Werf et al. 1993). We newly find that the line width at \(1^\circ - 2^\circ\) south of the S nucleus is even broader \((700 - 800\) km s\(^{-1}\) FWHM) than more northern regions. A reason why previous studies reported relatively narrow line width may be that the line width tends to be narrower at stronger \(H_2\) emission region and that they could only measure the intensity-weighted line width because of their insufficient spatial resolution. We also find...
that the line profile at this region shows boxy profile (with nearly flat-topped profile and relatively weak low intensity wing) rather than an usual Gaussian-like profile seen in more northern regions (Figure 4). In order to understand this peculiar line profile, we try to represent the observed spectra with the combination of two velocity components each of which is blue- and redshifted with respect to the mean central velocity measured with the single Gaussian fitting (Figure 3). We assume Gaussian line profile with the line width of 550 km s$^{-1}$ FWHM for each component. For simplicity, the intensities of the two components are set to be equal because of the nearly symmetric line profile (except for the low intensity blueshifted high-velocity wing component). The central velocity is set to $V_{sys} = 100$ km s$^{-1}$ from Figure 3. The fitting was made by eye. As a result, we find that superposition of the two components with a velocity difference of 500 km s$^{-1}$ can represent the observed line profile at 7$''$ south of the S nucleus (Figure 5). We thus propose a model that two broad (550 km s$^{-1}$ FWHM) emission lines whose velocity difference is $\approx 500$ km s$^{-1}$ make the boxy profile seen in the southern region. Note that the velocity difference of the two components (500 km s$^{-1}$) is nearly twice the velocity of the C-shaped velocity distortion observed around the S nucleus (250 km s$^{-1}$).

The line width of the Br$\gamma$ emission is nearly the same as that of the 1$−$0 S(1) emission (i.e., $\approx 500−600$ km s$^{-1}$ FWHM) at all positions with a detectable Br$\gamma$ emission. We find no kinematic evidence for the presence of a broad line region of AGN (5000 km s$^{-1}$ FWHM; Osterbrock 1989).

Emission-line ratios and the excitation mechanism

We examine the H$_2$ excitation mechanism at various positions. Following Mouri (1994), we show a line-ratio diagnostic diagram for discussing the excitation mechanisms in Figure 6. Some data points scatter around a theoretical locus of the thermal excitation with a temperature of about 2000 K. Others show slightly lower $1−0$ S(2)/1$−0$ S(0) ratio and scatter around observed data points of supernova remnants (SNRs). It is known that temperature gradient within the shock front causes the ratio slightly lower than this locus in SNRs (e.g., Beckwith et al. 1983). Thus, the molecular gas is thermally excited at most positions. On the other hand, we find no evidence for the non-thermal excitation with the larger 2$−1$ S(1)/1$−0$ S(1) ratio (0.5) anywhere.

We also show population diagrams at various positions (Figure 7). We find that the data points at each position are aligned along a single straight line on this diagram, indicating that thermal excitation is dominated at most positions. The region at $1''−1.25''$ south of the S nucleus marginally shows relatively stronger $1−0$ S(1) and weaker $2−1$ S(3) emissions. Figure 8 shows a spatial variation of the $v = 2−1$ vibration temperature ($T_{vib}$) and $v = 1$ rotation temperature ($T_{rot}$). Most regions show a temperature of $\sim 2000$ K, being consistent with the results of Sugai et al. (1997). In order to assess a possible contribution of other excitation mechanisms, we show a plot of the ratio of $T_{vib}$ to $T_{rot}$ as a function of slit positions (Figure 8). The ratio should be unity in case of a pure thermal excitation and be slightly larger in shocks with a temperature gradient (which is empirically $\approx 1.25 = 1/0.8$; Tanaka et al. 1991). In case of an UV fluorescent, the ratio becomes much larger than unity since $T_{vib}$ ($\approx 6000$ K) is much larger than $T_{rot}$ ($\sim 1000$ K) (e.g., Tanaka et al. 1991). Although the ratio is larger than unity at some positions, it can be understood as a case with a temperature gradient at most positions. The $1−0$ S(1) emission at $1''−1.25''$ south of the S nucleus shows slightly enhanced ratio of $T_{vib}$ to $T_{rot}$ although it is still consistent within errors with the thermal excitation with a temperature gradient. However, because the depression of the $2−1$ S(3) emission is also observed as well as the enhanced $1−0$ S(1) emission, UV fluorescent might contribute the H$_2$ emission to some extent there.

Discussion

Superwind origin of the H$_2$ emission

We find the three velocity components in the H$_2$ emission in the southern region of NGC 6240: 1) the blueshifted component ($\approx −250$ km s$^{-1}$ with respect to $V_{sys}$) which is recognized as a distinct C-shape distortion of the velocity field, 2) the high-velocity “wing” component ($\approx −1000$ km s$^{-1}$ with respect to $V_{sys}$), and 3) the component indicating possible line splitting of $\sim 500$ km s$^{-1}$. In the following sections we focus on these kinematic properties and discuss the origin of the extremely intense H$_2$ emission of NGC 6240 in the course of a “superwind” hypothesis.

Evidence for superwind

First we discuss the origin of the high-velocity “wing” component ($\sim −1000$ km s$^{-1}$ with respect to $V_{sys}$). It is difficult for the galaxy-galaxy collision at a speed of $75−200$ km s$^{-1}$ (van der Werf et al. 1993) to produce a high-velocity material at a speed up to $\sim 1000$ km s$^{-1}$ (van der Werf et al. 1993). Moreover, such
a component is only found around the S nucleus and the southern region, not around the region between the two nuclei where the two galaxies are likely to collide with each other. Thus, the galaxy-galaxy collision would not be responsible for this component. On the other hand, superwind origin of such a high-velocity material is promising since broad optical emission lines are detected around nuclear 1 kpc region in this galaxy and is attributed to the superwind on the basis of morphological, kinematic, and spectral evidence (Heckman et al. 1990).

The possible line splitting seen in the southern region can also be attributed to the superwind activity. Such type of the velocity field is often observed in the region of the expanding shell-like structure or biconical outflow seen in most superwind galaxies (e.g., Heckman et al. 1990). Most previous authors noted the extended south-south-west component 1" – 2" away from the S nucleus (Elston & Maloney 1990; Herbst et al. 1990; van der Werf et al. 1993). Because this region is located at another side of the interface between the two colliding galaxies and no energy source is detected such as a star-formation activity there, superwind activity would be a most plausible agent for exciting the molecular gas in this region. The region showing line splitting corresponds spatially to this component, suggesting that a superwind indeed affects the molecular gas at this region. Slight blueshift in this region (−100 km s⁻¹) can be understood if we assume that the expanding direction of the bubble is not within the sky plane but is slightly tilted to our line-of-sight. It is interesting that the CO emission also extends toward this direction and shows broader emission line profile like 1 – 0 S(1) emission (Tacconi et al. 1999), indicating that both of the cold (traced by CO) and the warm (traced by 1 – 0 S(1)) molecular gas is affected by the superwind activity.

The C-shaped velocity field around the S nucleus strongly support the idea that the H₂ emitting gas is affected by the superwind activity. There are some nearby examples showing cold gas (atomic and molecular gas) outflow at a speed of several hundred km s⁻¹ (e.g., Phillips 1993; Nakai et al. 1987; Ohyama & Taniguchi 1997). Theoretical calculations also predict such an expanding structure (e.g., Suchkov et al. 1994). It is expected that some of the gas entrained in the high-velocity ionized gas outflow would be heated up by the shock to form a shell with the intense H₂ emission. If there is an expanding shell around the S nucleus, the redshifted component would be obscured by the heavy dust extinction around the S nucleus. As noted before, the dust extinction is severe even in K band (A_k 22 mag), which is dusty enough to obscure the H₂ emission from behind the nucleus and only blueshifted velocity structure is expected to be observed. Although the peak position of the molecular gas is located around 0.−2pt²6 north of the S nucleus, significant fraction of the gas is distributed around the S nucleus (Tacconi et al. 1999). We expect that the column density around the S nucleus is still enough to obscure the redshifted part of the H₂ emission. i.e., the velocity field would be C-shaped. This type of a velocity structure is one of the common characteristics seen in galaxies with superwinds (e.g., Heckman et al. 1990).

Since it is well known that this galaxy actually exhibits a superwind activity (e.g., Heckman et al. 1987, 1990; Armus et al. 1990; Keel 1990), it is natural to attribute these three velocity components to the entrained and shocked molecular gas within the superwind. Because both of the high-velocity wing component and the line splitting is not detected around the N nucleus, the starburst and the superwind of the S nucleus would be responsible for exciting these components. This interpretation is supported by the fact that the [Fe II]λ 1.64μm emission, which is considered to arise at a shock driven by supernova explosions (van der Werf et al. 1993; Sugai et al. 1997), is much stronger at the S nucleus than at the N nucleus. All these considerations lead us to conclude that most H₂ emission in the southern region comes from the H₂ gas entrained in and shocked by the superwind blowing from the S nucleus.

Recently, Tacconi et al. (1999) conducted a high-resolution ¹²CO(J = 2 − 1) mapping. They found a velocity gradient along the position angle of ∼ 45° and showed the presence of blueshifted (∼ −350 km s⁻¹) with respect to their V_{sys} = 7320 km s⁻¹) molecular gas around the S nucleus. The trend of this gradient is similar to that found in the 1 − 0 S(1) emission (van der Werf et al. 1993). The peak position of the blueshifted CO emission (V_{sys} 6805 − 7005 km s⁻¹) is located at just ∼ 0.−2pt²2 north of the S nucleus, indicating the presence of the blueshifted cold molecular gas around the S nucleus. Thus, it is very likely that some part of the cold molecular gas traced with the CO emission is heated up by the shock driven by the superwind to emit blueshifted 1 − 0 S(1) emission around the S nucleus.

Evidence against galaxy-galaxy collision
In spite of many pieces of evidence for the superwind origin of the H$_2$ emission, we find no evidence for the galaxy-galaxy collision origin of the strong 1 − 0 S(1) emission. In the collision model, kinetic energy released by the global collision of the two nuclei is converted to 1 − 0 S(1) emission. Thus, most intense 1 − 0 S(1) emission is expected to arise from the collision interface. We, however, find that the peak of the emission is located much closer to the S nucleus, being inconsistent with the model prediction. In addition to the discussion on the flux distribution, the kinematic information gives another clue against the collision model. We find a C-shaped velocity distortion of the H$_2$ emission at a maximum blueshifted velocity of −250 km s$^{-1}$ around the S nucleus. On the other hand, the stellar velocity difference between the two nuclei is less than 75 km s$^{-1}$ (Lester & Gaffney 1994), indicating that only emission line component is blueshifted around the S nucleus. The stellar heliocentric velocity reported by Lester & Gaffney (1994) is $V_{r}$ = 7275 ± 50 km s$^{-1}$ and is consistent with the H$_2$ emission velocity measured around the N nucleus. We thus confirm that the emission line component around the S nucleus is blueshifted with respect to the stellar one. Thus, any models in which the H$_2$ emission is associated with the stellar component of the S nucleus can be rejected. Moreover, although some kind of a violent dynamical structure is expected at the interface of the two nuclei in the collision model, such as a sudden velocity change and/or a large velocity dispersion, such evidence is found neither around the region between the two nuclei where two galaxies are likely to be colliding nor other regions along the slit. In spite of these difficulties in the collision model, a superwind model can easily explain the velocity field, i.e., an expanding shell-like structure whose redshifted part is obscured by the heavy dust extinction on the extended H$_2$ gas with a nearly flat velocity field. Hence, we argue that the galaxy-galaxy collision would not be a main agent of the strong 1 − 0 S(1) emission of NGC 6240. Note, however, that we cannot reject a possibility of the galaxy-galaxy collision model since all pieces of evidence described above are not direct ones.

Spatial and dynamical structure of the superwind

Theoretical calculations predict that a superbubble is formed at the early stage of the superwind evolution and that it will break out to form a biconical structure when the bubble extends large enough compared with the scaleheight of the surrounding material (Tomisaka & Ikeuchi 1988; Heckman et al. 1990; Suchkov et al. 1994). The superbubble is originally spherical around the starburst nucleus and will elongate into the direction where the density gradient is the largest (Tomisaka & Ikeuchi 1988; Suchkov et al. 1994). This direction is usually perpendicular to the dense disk gas in case of the normal nuclear starburst in spiral galaxies. In the case of NGC 6240, however, this would not be the case since the surrounding matter is expected to be highly disturbed in the course of the merging process, leading to the complicated superwind structure as observed (e.g., Heckman et al. 1987; Armus et al. 1990; Keel 1990). Thus, it is important to discuss the superwind morphology and the velocity structure in detail in order to know the distribution of the ambient matter and to understand how the superwind interacts with this gas.

As pointed out before, the emission line structure is not symmetric around the S nucleus. Rather, the emission is extended farther to the south of the S nucleus (∼ 3″, or 1.4 kpc) than to the north (∼ 1″, or 450 pc). At the south region, we find a kinematic evidence for the expanding structure (i.e., the high-velocity wing component and the line splitting). It is difficult to say clearly whether the southern region shows a closed bubble-like structure or an open conical structure because of the low surface intensity of the 1 − 0 S(1) emission. At the north of the S nucleus, the emission line velocity goes back to $V_{sys}$ at just ∼ 1″ north of the S nucleus. A compact expanding bubble can explain such a property in which the bubble is expanding to the north in the sky plane and the line-of-sight expanding velocity becomes to be zero at the top of the bubble. Hence, a highly asymmetric elongated bubble/wind expanding to north-south direction within the sky plane would be a most likely picture of the superwind of NGC 6240.

Here we compare the observed size and velocity of the bubble with that of the theoretical expectations. Following Heckman et al. (1996), we assume an idealized model of a single spherical bubble within the uniform surrounding medium ($n_0$). The kinetic energy ($L_{mech}$) is assumed to be injected at a constant rate during a time ($t$) and the radiative losses are negligible. In this case, the radius ($r$) and the expanding velocity ($v$) can be expressed as equation $L_{mech} = 8 \times 10^{42} L_{bol,11}$ ergs s$^{-1}$,