Interaction between the north-eastern boundary of Sgr A East and giant molecular clouds

Sungho Lee,1,2 Soojong Pak,1,2★ Christopher J. Davis,3 Robeson M. Herrnstein,4 T. R. Geballe,5 Paul T. P. Ho4 and J. Craig Wheeler6

1Astronomy Programme in SEES, Seoul National University, Shillim-Dong, Kwanak-Gu, Seoul 151-742, South Korea
2Korea Astronomy Observatory, Whaam-Dong, Yuseong-Gu, Taejon 305-348, South Korea
3Joint Astronomy Centre, University Park, 660 North A’ohokū Place, Hilo, HI 96720, USA
4Harvard–Smithsonian Center for Astrophysics, 60 Garden Street, Cambridge, MA 02138, USA
5Gemini Observatory, 670 N. A’ohokū Place, Hilo, HI 96720, USA
6Astronomy Department, University of Texas, Austin, TX 78712, USA

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ABSTRACT

We have detected the $v = 1 \rightarrow 0$ $S(1)$ ($\lambda = 2.1218$ $\mu$m) and $v = 2 \rightarrow 1$ $S(1)$ ($\lambda = 2.2477$ $\mu$m) lines of $H_2$ in the Galactic Centre, in a $90 \times 27$ arcsec$^2$ region between the north-eastern boundary of the non-thermal source Sgr A East, and the giant molecular cloud (GMC) M−0.02 − 0.07. The detected $H_2$ $v = 1 \rightarrow 0$ $S(1)$ emission has an intensity of $1.6–21 \times 10^{-18}$ $W$ m$^{-2}$ arcsec$^{-2}$ and is present over most of the region. Along with the high intensity, the large linewidths (FWHM = 40–70 km s$^{-1}$) and the $H_2v = 2 \rightarrow 1$ $S(1)$ to $v = 1 \rightarrow 0$ $S(1)$ line ratios (0.3–0.5) can be best explained by a combination of C-type shocks and fluorescence. The detection of shocked $H_2$ is clear evidence that Sgr A East is driving material into the surrounding adjacent cool molecular gas. The $H_2$ emission lines have two velocity components at ~+50 and ~0 km s$^{-1}$, which are also present in the NH$_3$(3, 3) emission mapped by McGary, Coil & Ho. This two-velocity structure can be explained if Sgr A East is driving C-type shocks into both the GMC M−0.02 − 0.07 and the northern ridge of McGary et al.

Key words: ISM: individual: Sgr A East – ISM: individual: M−0.02 − 0.07 – ISM: lines and bands – ISM: molecules – Galaxy: centre – infrared: ISM.

1 INTRODUCTION

Sgr A East has frequently been interpreted as a supernova remnant because of its shell structure and non-thermal spectrum (Jones 1974; Goss et al. 1983 and references therein; and see the more recent references in Maeda et al. 2002). Some recent research, however, has suggested that the energetics, size, and elongated morphology (3 × 4 arcmin$^2$ or 7 × 9 pc$^2$ at $d = 8.5$ kpc) of Sgr A East cannot have been produced by a typical supernova (Yusef-Zadeh & Morris 1987; Mezger et al. 1989). Mezger et al. (1989) estimate the required energy to produce Sgr A East to be more than $4 \times 10^{52}$ erg. Modelling of the entire spectrum of Sgr A East by Fatuzzo et al. (1999), which fits very well with the observations of the non-thermal emission of Sgr A East and EGRET $\gamma$-ray sources, supports the energy estimate by Mezger et al. (1989). Those authors concluded that a single supernova explosion could explain the existence of Sgr A East only if it occurred within the cavity formed by the stellar wind from a progenitor star. In that scenario, however, the formation of the cavity takes too much time ($\sim 10^3$ yr) compared with the orbital period ($\sim 10^5$ yr) of matter circling around the Galactic Centre (Mezger et al. 1989).

Yusef-Zadeh & Morris (1987) suggested that a different kind of explosive event could create Sgr A East. The energy required to make a huge shell such as Sgr A East has been associated with a ‘hypernova’ (Woosley, Eastman & Schmidt 1999). Khokhlov & Melia (1996) hypothesize that Sgr A East may be the remnant of a solar-mass star tidally disrupted by a massive black hole. Their model can naturally explain the elongated shape of Sgr A East as well as the extreme energetics. However, from their observation with the Chandra X-ray Observatory, Maeda et al. (2002) suggest that Sgr A East should be classified as a metal-rich ‘mixed morphology’ supernova remnant. They argue that the model of Khokhlov & Melia (1996) cannot reproduce the metal-rich abundances observed at the centre of Sgr A East. They also conclude that a single Type II supernova explosion with an energy of $10^{51}$ erg into a homogeneous ambient medium with a density of $10^3$ cm$^{-3}$ can most simply explain the results of both radio and X-ray observations, and thus that the extreme energy of $\sim 10^{52}$ erg is not required.

In principle, the energy of the explosive event can be directly measured by studying regions where Sgr A East is colliding with

★E-mail: soojong@kao.re.kr

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ambient interstellar material. By tracing the dynamics of molecular gas, an interaction between the eastern part of Sgr A East and the giant molecular cloud (GMC) M–0.02 – 0.07 (also known as the ‘50 km s$^{-1}$ cloud’) has been inferred (Genzel et al. 1990; Ho et al. 1991; Serabyn, Lacy & Achtermann 1992; Mezger, Duschl & Zylka 1996; Novak 1999; Coil & Ho 2000). Recent observations of NH$_3$(3,3) emission in the region show that Sgr A East impacts material to the north and west as well (see Fig. 1) (McGary, Coil & Ho 2001). As direct evidence of this interaction, several 1720-MHz OH masers, which are a good diagnostic of the continuous, or C-type, shock excitation (Frail et al. 1996; Wardle, Yusef-Zadeh & Geballe 1999), have been detected along the southern edge of Sgr A East and to the north of the circumnuclear disc (CND) (Yusef-Zadeh et al. 1996).

Wardle et al. (1999) and Yusef-Zadeh et al. (1999b, 2001) detected H$_2$ line emission in regions where OH masers have been detected. In most cases H$_2$ line emission arises either from thermal excitation (e.g. by shock heating) or from non-thermal excitation by far-ultraviolet absorption (Black & van Dishoeck 1987; Burton 1992; Pak et al. 1998). One can in principle distinguish between these two mechanisms by comparing near-infrared (near-IR) line intensities. The H$_2$ $v = 2 \rightarrow 1$ S(1)/$v = 1 \rightarrow 0$ S(1) ratio has been an effective discriminant in a number of shocked regions (where the ratio should be $\lesssim 0.3$) and photodissociation regions (PDRs) (where it is about 0.5–0.6). However, a ‘thermal’ line ratio can be observed in a PDR – even though fluorescence is the dominant excitation mechanism – if the gas density is high ($\gtrsim 10^5$ cm$^{-3}$; Sternberg & Dalgarno 1989). Gatley et al. (1984) observed the CND and concluded that the H$_2$ molecules are excited by collisions, while the results for larger regions (about 2$''$ × 2$''$) by Pak, Jaffe & Keller (1996a,b) are consistent with non-thermal excitation. The interpretation of Wardle et al. (1999) and Yusef-Zadeh et al. (1999b, 2001) that the line emission in Sgr A East is thermal is supported by the presence of the 1720-MHz OH masers. It is therefore likely that Sgr A East is indeed driving shocks into the adjacent GMCs to the south and into the CND.

The fields observed by Wardle et al. (1999) and Yusef-Zadeh et al. (1999b, 2001) are restricted to the vicinity of the CND and cover only some of the regions where interaction of the Sgr A East shell with surrounding material is expected. Before one can hope to estimate the energy released in the event that created Sgr A East, it is necessary to observe additional interaction regions in diagnostic lines of H$_2$ at high spectral resolution. In this paper we present velocity-resolved, near-IR H$_2$ observations at the north-eastern boundary of Sgr A East. By measuring H$_2$ $v = 2 \rightarrow 1$ S(1)/$v = 1 \rightarrow 0$ S(1) line ratios and line profiles simultaneously, we aim to study the excitation and kinematics of the interaction between Sgr A East and M–0.02 – 0.07.

2 OBSERVATION AND DATA REDUCTION

We observed the H$_2$ $v = 1 \rightarrow 0$ S(1) ($\lambda = 2.1218$ $\mu$m) and the H$_2$ $v = 2 \rightarrow 1$ S(1) ($\lambda = 2.2477$ $\mu$m) spectra at the 3.8-m United Kingdom Infra-Red Telescope (UKIRT) in Hawaii on 2001 August 3 and 4 (UT), using the Cooled Grating Spectrometer 4 (CGS4; Mountain et al. 1990) with a 31 line mm$^{-1}$ echelle grating, 300-mm focal length camera optics and a two-pixel-wide slit. The spatial resolution along the slit was 0.90 arcsec for H$_2$ $v = 1 \rightarrow 0$ S(1)
with a grating angle of 64:691 and 0.84 arcsec for \( H_2 \) \( v = 2 \rightarrow 1 \) \( S(1) \) with a grating angle of 62:127; the slit widths on the sky were 0.83 and 0.89 arcsec, respectively, for these two configurations. The slit length was \( \sim 90 \) arcsec. The instrumental resolutions, measured from Gaussian fits to sky lines in our raw data, were \( \sim 17 \) km s\(^{-1}\) for \( H_2 \) \( v = 1 \rightarrow 0 \) \( S(1) \) and \( \sim 19 \) km s\(^{-1}\) for \( H_2 \) \( v = 2 \rightarrow 1 \) \( S(1) \).

10 parallel slit positions were observed, sampling a 90 × 27 arcsec\(^2\) area on the north-eastern boundary of Sgr A East. The slit was oriented 40° east of north for each measurement; adjacent slit positions were separated by 3 arcsec perpendicular to the slit axis. The coordinates at the centre of the observed area are \( \alpha = 17^{h}45^{m}45.9^{s}, \delta = -28^{\circ}59^{\prime}05^{\prime\prime} \) (J2000) (see Fig. 1). The south-western part of this region includes the ‘outer H\(_2\) clumps’ from which \( H_2 \) emission was detected by Yusef-Zadeh et al. (2001). Only the ninth slit position, hereafter called ‘slit 9’, was observed in both \( H_2 \) \( v = 1 \rightarrow 0 \) \( S(1) \) and \( H_2 \) \( v = 2 \rightarrow 1 \) \( S(1) \). The telescope was nodded between object and blank-sky positions every 25 min, to subtract the background and telluric OH line emission. The sky positions were offset by about 2.5 (\( \Delta \alpha = -2.03, \Delta \delta = 0.85 \)) from the on-source positions.

Initial data reduction steps, involving bias-subtraction and flat-fielding (using an internal blackbody lamp), were accomplished by the automated Observatory Reduction and Acquisition Control (ORAC) pipeline at UKIRT. IRAF was used for the remainder of the reduction. We corrected the spectral distortion along the dispersion axis using the spectrum of the standard star HR 6496 as a template. The sky OH lines were then used to correct for spatial distortion perpendicular to this axis and also for wavelength calibration. We also corrected for the motions of the Earth and Sun in order to determine local standard of rest (LSR) velocities.

Only part of the flux from a standard star is detected because of the narrow slit; hence for proper flux calibration the measured signal must be corrected. We assumed a circularly symmetric point spread function (PSF) for the star, based on the flux profile along the slit length, to estimate the missing flux. The correction factor, which varies with the seeing, ranged from 2.06 to 2.56. Near-IR emission from the Galactic Centre is attenuated by interstellar material in the foreground (mostly 4–8 kpc from the Galactic Centre) and by material in the Galactic Centre itself. Since we believe that the \( H_2 \) line emission originates from the surface of the cloud, we ignore the latter (Pak et al. 1996a,b) and correct only for foreground extinction, which we assume to be \( A_K = 2.5 \) mag (Catchpole, Whitelock & Glass 1990).

3 RESULTS AND DISCUSSION

3.1 \( H_2 \) \( v = 1 \rightarrow 0 \) \( S(1) \) emission

Bright (1.6–21 × 10\(^{-18}\) W m\(^{-2}\) arcsec\(^{-2}\)) \( H_2 \) emission was detected from most of the observed region (90 × 27 arcsec\(^2\)) along the north-eastern boundary of Sgr A East. We created a south-east–north-west cut parallel to the boundary of Sgr A East (‘cut B’) by extracting spectra from each of the 10 slit positions. A second cut perpendicular to the boundary (i.e. south-west–north-east) is composed of six positions from slit 9. The positions of cut B and slit 9 are marked in Fig. 1. Along cut B, the intensity of \( NH_3 \) emission varies dramatically; we can investigate both high- and low-density regions along this cut. Slit 9 is the only slit observed in both \( H_2 \) \( v = 1 \rightarrow 0 \) \( S(1) \) and \( v = 2 \rightarrow 1 \) \( S(1) \), the line ratio of which we can use to constrain models for the excitation of \( H_2 \). In this paper, we present the results of these two cuts, rather than the whole data set, as a preliminary report. We aim to concentrate on the excitation mechanism of the detected \( H_2 \) emission, and to map the structure and kinematics perpendicular to and parallel to the boundary. From the 16 \( H_2 \) \( v = 1 \rightarrow 0 \) \( S(1) \) spectra in Figs 2 and 3 we measure line centres and linewidths along the interaction region. Each spectrum is well fitted by one or two Gaussian components.

Figs 4 and 5 show the distributions of the derived \( H_2 \) \( v = 1 \rightarrow 0 \) \( S(1) \) line parameters along cut B and slit 9, respectively. For direct comparison, we include in these figures data from the \( NH_3 \) (3, 3) observations of McGary et al. (2001); the \( NH_3 \) emission essentially traces the cool (\( \lesssim 100 \) K), dense (\( 10^5 \) cm\(^{-3}\)) cloud material. From these data we note the following.

(i) In Figs 4(a) and 5(a) there are two velocity components, at \( V_{LSR} \sim 0 \) and \( \pm 50 \) km s\(^{-1}\). Both components are evident in \( H_2 \) and \( NH_3 \), although the 0 km s\(^{-1}\) features are not spatially coincident. The variation in the velocity of either component is less than \( \pm 20 \) km s\(^{-1}\) along both slit 9 and cut B.

(ii) The \( H_2 \) linewidths in Figs 4(b) and 5(b) are much larger than the \( NH_3 \) widths and show no obvious trend along either slit 9 or cut B.

(iii) Along cut B, the distribution of the total intensity of \( H_2 \) (the solid line in Fig. 4c) is quite different from that of \( NH_3 \) (the dashed line). The \( NH_3 \) emission increases to the south-east as the cut passes deeper into the body of the GMC \( M \sim 0.02 – 0.07 \), but the \( H_2 \) emission decreases in this direction. The decrease in \( H_2 \) may be explained by exhaustion of the source of excitation (e.g. shock energy or ultraviolet photons) or by obscuration, at the inner, more dense regions of the cloud, or by the geometry of the interaction region (see Section 3.3).

(iv) Along slit 9, the distribution of the \( H_2 \) intensity (solid line) in Fig. 5(c) is generally similar to that of \( NH_3 \) (dashed line). It should be noted that \( NH_3 \) is attenuated at positions greater than \( +30 \) arcsec by the edge of the primary beam in the Very Large Array (VLA) mosaic (McGary et al. 2001). There is a small discrepancy between \( NH_3 \) and \( H_2 \) between +10 and +30 arcsec which may be the result of the same effects discussed for cut B. Note that slit 9 covers a very large spatial scale (90 arcsec). The brightest emission along slit 9, between offsets –20 and –45 arcsec (the south-western part), arises from the outer \( H_2 \) clumps of Yusef-Zadeh et al. (2001).

3.2 \( H_2 \) excitation

The \( H_2 \) \( v = 2 \rightarrow 1 \) \( S(1) \) line was detected at three locations along slit 9, at positions 23.7 arcsec north-east, 10.5 arcsec south-west and 22.2 arcsec south-west relative to the centre of the slit (\( \alpha = 17^{h}45^{m}45.3^{s}, \delta = -28^{\circ}58^{\prime}58^{\prime\prime} \) (J2000). From these data we measured line ratios \( [H_2 \ v = 2 \rightarrow 1 \ S(1)/v = 1 \rightarrow 0 \ S(1)] \) of 0.40 ± 0.12, 0.51 ± 0.17 and 0.27 ± 0.07, respectively (see Fig. 3). At other positions only the \( H_2 \ v = 1 \rightarrow 0 \ S(1) \) line was detected, with 3\( \sigma \) upper limits to the ratio of 0.5, 0.6 and 0.1 at offsets of 31.8 arcsec north-east, 4.8 arcsec north-east and 44.7 arcsec south-west along slit 9, respectively.

Fluorescent excitation in a low-density PDR \( [n(H_2) < 5 \times 10^4 \) cm\(^{-3}\)] should yield a ratio of about 0.6. A lower ratio is expected in a more dense PDR environment (Black & van Dishoeck 1987), or in a shock. There are two basic types of shock: ‘jump’ or J-type and ‘continuous’ or C-type (see Draine & McKee 1993 for a review). A J-type shock is formed in a highly ionized or weakly magnetized gas. Fluid parameters such as density and temperature undergo a discontinuous change (jump) at the shock front where the molecules may be dissociated. J-type shocks (with velocities greater
than about 24 km s\(^{-1}\)) will completely dissociate the molecules (Kwan 1977); \(\text{H}_2\) emission occurs from a warm, recombination plateau in the post-shock region. J-type shocks typically produce low line intensities and \(\text{H}_2\) \(v = 2 \rightarrow 1\ S(1)/v = 1 \rightarrow 0\ S(1)\) line ratios as large as 0.5 are possible (Hollenbach & McKee 1989). At lower shock velocities, below the \(\text{H}_2\) dissociation speed limit, J-type shocks may yield much lower line ratios: \(<0.3\) (Smith 1995).

In a C-type shock, where the magnetic field softens the shock front via ion–magnetosonic wave propagation so that the fluid parameters change continuously across the shock front, the \(\text{H}_2\) dissociation speed limit is much higher (\(\sim 45\) km s\(^{-1}\), depending on the density and magnetic field strength in the pre-shock gas). Smaller line ratios of about 0.2 are then predicted (Smith 1995; Kaufman & Neufeld 1996).

From the observed ratios alone we are not able to distinguish unambiguously between excitation mechanisms. Our results can be explained by fast J-type shocks or dense PDRs, or by a combination of fluorescence and either C-type shocks or slow J-type shocks, since the higher line ratios associated with fluorescence will be tempered by the low \(\text{H}_2\) \(v = 2 \rightarrow 1\ S(1)\) intensities associated with collisional excitation in shocks.

To help to distinguish between the \(\text{H}_2\) excitation mechanisms, we consider kinematic information and the spatial variation of the line ratio along slit 9. At most positions in Figs 4(b) and 5(b), the \(\text{H}_2\) linewidths are high (typically 40–70 km s\(^{-1}\), but as high as 120 km s\(^{-1}\) in some positions). This suggests shock excitation and turbulent motions in the gas and tends to exclude the pure fluorescence models (in which the \(\text{H}_2\) line emission generally arises from the stationary gas at the edges of neutral clouds illuminated by far-ultraviolet photons from early-type stars). However, in other shocked regions the line ratio is found to be constant over a wide range of \(\text{H}_2\) \(v = 1 \rightarrow 0\ S(1)\) intensities and spatial positions (Davis & Smith 1995; Richter, Graham & Wright 1995), although this is not necessarily predicted from theory (Draine & McKee 1993). Conversely, in a PDR the ratio is sensitive to the incident far-ultraviolet flux and the molecular gas density [the \(\text{H}_2\) \(v = 1 \rightarrow 0\ S(1)\) intensity increases but the \(\text{H}_2\) \(v = 2 \rightarrow 1\ S(1)/v = 1 \rightarrow 0\ S(1)\) ratio decreases with increasing gas density or ultraviolet intensity: Usuda et al. 1996; Takami et al. 2000].

Thus an unchanging \(\text{H}_2\) \(v = 2 \rightarrow 1\ S(1)/v = 1 \rightarrow 0\ S(1)\) ratio is found in shocks, while a varying ratio is expected in the pure fluorescent case. The measured line ratio and the \(\text{H}_2\) \(v = 1 \rightarrow 0\ S(1)\) intensity in Fig. 5(c) show evidence of an anti-correlation in our data, as expected in dense PDRs. Although the wide line profiles point to shock excitation, fluorescence appears to play a significant role at least some locations.

Considering the kinematics further, we note that J-type shocks produce narrow lines which peak at the velocity of the shock, while C-type shocks produce broader lines which peak at the velocity of the pre-shock gas and extend up to the shock velocity. Figs 4(a) and 5(a) show that there are two velocity components that are similar in
H$_2$ and NH$_3$. The H$_2$ emission traces hot ($\sim$2000 K) gas and the NH$_3$ cool ($\lesssim$100 K) gas. Thus, if we assume that shocks are driven by Sgr A East into cold molecular gas with velocities given by the NH$_3$ data, then fast J-type shocks are inconsistent with our results, owing to the low peak velocities of the H$_2$ lines relative to the molecular clouds.

In summary, then, the wide line profiles and low peak velocities indicate C-type shock excitation. However, the high values of the line ratio at some positions along slit 9 and the spatial variation in that ratio point to a fluorescent component to the excitation in some locations. A combination of C-type shocks and fluorescence (see e.g. Fernandes, Brand & Burton 1997) is therefore the most reasonable explanation for the H$_2$ excitation. For the fluorescence, the source of the ultraviolet radiation could be either nearby early-type stars or J-type shocks. However, as noted above, we see no evidence of J-type shocks in our data. Also, we cannot establish whether nearby stars are the source of the ultraviolet flux owing to the lack of information on where or how many early-type stars there are in the region.

### 3.3 Structure of the interaction region

The extended $+$50 km s$^{-1}$ component of the NH$_3$ emission traces the GMC $M=0.02-0.07$, while the 0 km s$^{-1}$ component corresponds to the ‘northern ridge’ of McGary et al. (2001) [see the NH$_3$(3, 3) channel maps in their fig. 4]. The NH$_3$ component at $+$20 km s$^{-1}$ seen in Fig. 5(a) at negative offsets seems to trace hotter gas according to the NH$_3$(2, 2) to (1, 1) line ratio map by McGary et al. (2001), which they suggest may be the result of an impact by Sgr A East.

The difference in linewidth between NH$_3$ and H$_2$ as well as the different spatial locations of their 0 km s$^{-1}$ features (Fig. 5a) indicate that the NH$_3$ and H$_2$ trace fundamentally different components of the gas. The small NH$_3$ linewidths arise in ambient clouds. The broader H$_2$ line emission traces shocked gas where the NH$_3$ molecules are probably destroyed. One can envision a situation in which Sgr A East is located adjacent to both M$=0.02-0.07$ (the $+$50 km s$^{-1}$ component) and the northern ridge (the 0 km s$^{-1}$ component), with Sgr A East driving C-type shocks into these clouds.

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**Figure 3.** H$_2$ $v=1\rightarrow0$ S(1) and H$_2$ $v=2\rightarrow1$ S(1) spectra from six positions along slit 9. Indicated positions are relative to $\alpha=17^{h}45^{m}45^{s}$, $\delta=-28^{\circ}58^{'}58^{''}$ (J2000). The left-hand panels show the H$_2$ $v=1\rightarrow0$ S(1) spectra. The three right-hand panels present both the H$_2$ $v=1\rightarrow0$ S(1) and H$_2$ $v=2\rightarrow1$ S(1) spectra from the positions where H$_2$ $v=2\rightarrow1$ S(1) emission is detected; these are averaged over 3.4 arcsec on the sky to improve the signal-to-noise ratios. The other aspects are the same as for Fig. 2.
Figure 4. Derived line parameters for the spectra along cut B: (a) line centre velocity; (b) linewidth; and (c) integrated line intensity. Indicated positions are as in Fig. 2; positive towards the north-west. The filled circles and the open circles represent the +50 km s\(^{-1}\) component and the 0 km s\(^{-1}\) component of the H\(_2\) v = 1 \(\rightarrow\) 0 S(1) spectra, respectively, and the filled and open squares the +50 and 0 km s\(^{-1}\) components of the NH\(_3\)(3, 3), from McGary et al. (2001). In panel (c), the solid and dashed lines denote the total intensity of H\(_2\) v = 1 \(\rightarrow\) 0 S(1) and NH\(_3\)(3, 3), respectively, the latter scaled by 10\(^{-16}\). The range of our H\(_2\) observation is denoted by two vertical lines.

Figure 5. Derived line parameters for the spectra along slit 9. Indicated positions are as in Fig. 3; positive towards the north-east. Identities of plotted quantities are as in Fig. 4. The decrease in NH\(_3\) flux at positions greater than +30 arcsec is a result of reduced sensitivity at the edge of the mosaic (McGary et al. 2001).
On the other hand, the fact that the two $H_2$ velocity components overlap along the line of sight, yet are roughly equally bright, seems somewhat unlikely, as one must be attenuated by the molecular cloud associated with the other. The rough equality might be explained by clumpiness of the foreground cloud, regardless of which one is in the foreground, where a small filling factor of high-density clumps are embedded within a less dense medium (Burton, Hollenbach & Tielens 1990). The size of such clumps seems to be $10^{-4}$–$10^{-3}$ pc (Garay, Moran & Reid 1987; Churchwell et al. 1987), which is smaller than our resolution of $\sim 1$ arcsec ($\sim 4 \times 10^{-2}$ pc at the distance of $\sim 8.5$ kpc to the Galactic Centre). As illustrated in Fig. 6, this clumpy structure could explain both the observed decrease of $NH_3$ line emission and the observed increase of $H_2$ line emission toward the edge of the cloud [see the $+50$ km s$^{-1}$ components in Figs 4(c) and 5(c)].

4 CONCLUSION

We observed the north-eastern part of the Sgr A East shell in order to investigate its interaction with the GMC $M=0.02 - 0.07$. The bright $H_2$ $v = 1 \rightarrow 0$ S(1) emission is strong evidence that Sgr A East is physically adjacent to, and interacting with, $M=0.02 - 0.07$.

By comparing the relative intensities of $H_2$ $v = 1 \rightarrow 0$ S(1) and $H_2$ $v = 2 \rightarrow 1$ S(1) emission, the distribution of the $H_2$ $v = 2 \rightarrow 1$ S(1)/$v = 1 \rightarrow 0$ S(1) line ratio, and the radial velocities of the $H_2$ emission, we can to some extent distinguish between excitation mechanisms for the $H_2$. The line ratios tend to support emission in either fast J-type shocks or a dense PDR. However, on considering the bright $H_2$ $v = 1 \rightarrow 0$ S(1) intensity, the large linewidths and the spatial variation in the line ratio, we conclude that a combination of C-type shocks and fluorescence is required. The presence of shocks is direct evidence that Sgr A East is driving into the surrounding material, and is consistent with the detection of 1720-MHz OH masers to the north of the CND and to the south of Sgr A East (Yusef-Zadeh et al. 1996). Very recently Karlsson et al. (2003) detected the 1720-MHz OH masers also at two positions near our target region, which is more direct evidence supporting our conclusion on the C-type shocks.

The $H_2$ emission covers most parts of our targeted region ($90 \times 27$ arcsec$^2$). The line profiles are made up of two velocity components, both of which extend over a significant portion of the region ($15 \times 27$ arcsec$^2$). We find that the $NH_3(3, 3)$ emission lines observed by McGary et al. (2001) also show a similar kinematic structure, with almost the same velocities. We suggest that the $H_2$ line emission arises at the interfaces between Sgr A East and two independent molecular clouds, with line-of-sight velocities of $\sim +50$ km s$^{-1}$ ($M=0.02 - 0.07$) and $\sim 0$ km s$^{-1}$ (the northern ridge). Both the observed two velocity components of the $H_2$ emission and the difference in the intensity distributions between the $H_2$ and $NH_3$ emission can be understood if the molecular clouds are composed of small dense clumps with a very small filling factor.

To study the origin and evolution of Sgr A East, it would be important to know the total $H_2$ luminosity and the total cooling rate (based on that) over the interaction region, which could be compared with those of well-studied supernova remnants. However, it is very difficult to estimate them with the small amount of information that we have at present. Given the uncertainty in the emission mechanisms, even estimating the total $H_2$ luminosity in the small mapped region would be difficult, without considering the entire interaction region. It would be premature for us to estimate the required energy to make the Sgr A East shell. We will be able to do this in the future, after observations of more of the interaction region.

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