High Spectral and Spatial Resolution Observations of Shocked Molecular Hydrogen at the Galactic Center

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The presence of OH (1720 MHz) masers, and the absence of counterparts at 1665/1667 MHz has proved to be a clear diagnostic of shocked molecular gas associated with Galactic supernova remnants. This suggests that shocked molecular gas should be associated with the OH (1720 MHz) masers that have been detected in the circumnuclear disk (CND) and Sgr A East at the Galactic center. In order to test this hypothesis, we observed the H$_2$ 1–0 S(1) and Br $\gamma$ lines using NICMOS on the HST and UNSWIRF on the AAT, near the regions where OH (1720 MHz) masers are detected in the CND and Sgr A East. We present the distribution of H$_2$ in the North and South lobes of the CND and in Sgr A East. H$_2$ emission accompanies almost all of the maser spots detected at the Galactic center. In particular, we find a striking filamentary structure near the Northwest of the CND and evidence that shocked molecular gas is associated with the 70 kms$^{-1}$ molecular cloud at the Galactic center. We argue that the emission from the CND could arise in gas heated by the dissipation of the random motion of clumps by collisions or the dissipation of turbulence in a more homogeneous medium. In addition, highly red-shifted gas of up to 140 kms$^{-1}$ close to the eastern edge of the Sgr A East shell is detected. These observations combined with OH (1720 MHz) results suggest that the H$_2$ gas is shocked and accelerated by the expansion of Sgr A East into the 50 and the 70 kms$^{-1}$ cloud and into the lobes of the CND.

*Subject headings:* galaxies: ISM—Galaxy: center —ISM: individual (Sgr A*)
1. Introduction

The Galactic center provides a unique opportunity to study in detail the dynamics and physical conditions of the closest galactic nucleus. The picture that has emerged from multi-wavelength studies of the Galactic center over the last quarter of a century is that it contains a clumpy molecular ring (also known as the Circumnuclear Disk, or CND), as seen in HCN emission, on a scale of 2 to 5 pcs circling the Galactic center with a rotational velocity of about 100 \( \text{km} \cdot \text{s}^{-1} \) (see Jackson et al. 1993; Latvakoski et al. 1999 and references therein). The CND is heated by UV radiation from the hot stars within the central cavity. The peaks of molecular emission from the CND are located in its NE (N lobe) and SW (S lobe) and are consistent with limb-brightening of the inner edges along the principal axis of a ring. Within the ring’s central cavity, three “arms” of ionized gas (Sgr A West) are in orbital motion around the center (e.g. Roberts and Goss 1993; Serabyn and Lacy 1985), which is believed to contain a \( \sim 2.5 \times 10^6 \ M_\odot \) black hole (Eckart and Genzel 1996; Ghez et al. 1998). The coincidence in the geometry and kinematics of the southwestern edge of the molecular ring and ionized gas suggests that the ionized gas is dynamically coupled to the inner edge of the circumnuclear ring (e.g. Güsten et al. 1987).

On a larger scale a non-thermal structure, Sgr A East, is thought to be a shell-type explosive event, possibly a supernova remnant (SNR), surrounded by the 50 \( \text{km} \cdot \text{s}^{-1} \) molecular cloud. A number of observations present strong evidence that these two objects are physically interacting with each other (e.g. Mezger et al. 1996; Zylka et al. 1990; Serabyn et al. 1992; Yusef-Zadeh et al. 1996). Thus, the dynamical coupling of the thermal Sgr A West and the CND, as well as the nonthermal Sgr A East and the 50 \( \text{km} \cdot \text{s}^{-1} \) cloud, has been fairly well established. A question that will be addressed in this paper is the nature of the interaction between these two systems.

Observations of molecular hydrogen gas are useful, not only for determining the
dynamics of gas, but also for their potential to distinguish shocked from UV–excited gas. Molecular hydrogen line emission has been detected from the inner edge of the circumnuclear ring. The excitation is thought to be produced by shocks driven into the ring by the ram pressure associated with the outflow from the IRS 16 cluster (Gatley et al. 1986; Yusef-Zadeh and Wardle 1993). Broad emission lines observed toward the Galactic center could have contribution from outflows from the vicinity of the IRS 16 cluster with a terminal velocity $v_w = 500 - 700 \text{ km s}^{-1}$ and a mass-loss rate $\dot{M}_w \approx 4 \times 10^{-3} \ M_\odot \text{ yr}^{-1}$ (Hall, Kleinmann, & Scoville 1982; Geballe et al. 1991; Allen et al. 1990). However, the detection of shocked (as opposed to UV–heated) gas associated with the Galactic center molecular ring has been ambiguous. The intensity ratios of the $v=2–1$ and 1–0 $S(1)$ lines of molecular hydrogen (Gatley et al. 1986; Burton & Allen 1992, 1993; Ramsay-Howatt et al. 1993; Pak et al. 1996) are taken to be consistent with collisional excitation rather than fluorescence from low-density gas, but the high density of the molecular gas at the Galactic center and the intense UV radiation field in the region allow the line ratios from UV-irradiated gas to resemble those of shock-heated gas (Sternberg & Dalgarno 1989; Burton et al. 1990).

The OH molecule has recently proved to be useful in distinguishing shocked from radiatively excited molecular gas through the presence of 1720 MHz masers. The presence of the OH (1720 MHz) maser line, and the absence of the 1665/1667 MHz lines provides a clear diagnostic of shocked molecular gas, as the far–IR radiation field from warm dust in UV-heated clouds would pump the latter transitions (Frail, Goss & Slysh 1994; Lockett, Gauthier & Elitzur 1999). Recent detection of diffuse X-ray emission from the interior of Sgr A East and from Sgr A West are consistent with the shock model enhancing the abundance of OH behind the shock front (e.g. Baganoff et al. 2001; Maeda et al. 2001; Wardle 1999). The expansion of a supernova remnant into the Sgr A East molecular cloud (i.e. the 50 kms$^{-1}$ cloud) is believed to be responsible for the production of the OH (1720
MHz) maser emission (Yusef-Zadeh et al. 1996, 1999a). If the OH (1720 MHz) masers signify regions of shocked gas, this suggests that the H$_2$ emission is also shock-excited.

In order to investigate this hypothesis, observations of the H$_2$ 1–0 S(1) and Br $\gamma$ lines were carried out using the University of New South Wales Infra-Red Fabry-Perot (UNSWIRF) on the AAT and NICMOS on the HST near the regions where OH (1720 MHz) masers are detected in the CND and Sgr A East. The NICMOS data provide subarcsecond spatial resolution and the UNSWIRF data provide velocity information for both the molecular and ionized gas. Preliminary results of these observations combined with low-frequency radio continuum images were presented by Yusef-Zadeh et al. (1999b) who argued for the interaction of Sgr A East and the CND.

This paper presents the distribution of H$_2$ gas in the CND in section 3.1 and discusses the nature of H$_2$ gas in section 3.2 followed by the correlation of H$_2$ linear feature, OH (1720 MHz) masers, the Sgr A East molecular cloud and radio continuum emission from Sgr A East with each other in section 3.3 and 3.4. In particular, the evidence is presented that the H$_2$ linear filament to the NW of the CND is not only excited by Sgr A East but also is associated with the CND by a ridge of molecular gas. We then present the evidence that all Galactic center OH (1720 MHz) masers, with one exception, are accompanied by shocked H$_2$ gas with the implication that Sgr A East is responsible for shocking the gas in the CND, the 50 and the 70 km s$^{-1}$ molecular clouds. In section 3.5, two extinction clouds are discussed toward the Northern Arm and Sgr A East before conclusions are drawn in section 4.
2. Observations

Camera 3 of NICMOS on the HST was used to observe the 1-0 S(1) transition of H$_2$ toward Sgr A West as well as Sgr A East. Twelve adjacent pointings, each with a 52" field of view and 0.203" pixel scale, were observed in 1% bandwidth filters containing the line+continuum (F212N) and continuum (F215N). The observations were made on July 3 and 4, 1998 when the plate scale for camera 3 was 0.20384” x 0.20310” along the detector axes in x and y, respectively. Because the majority of the images had to be rotated by ~135 degrees to orient north up, the x and y plate scales were effectively equally interpolated to an average value of 0.2035”/pixel without the need to correct for non-square pixels. The individual pointings were additionally dithered 4 times in a square pattern spaced by 16” along the detector axes in order to provide spatial overlap, correct for bad pixels, and to improve the sampling. Final mosaics covering ~ 4’ × 4’ were constructed by combining all 48 frames in each filter. Each of the 48 positions was observed for 128 seconds using a MULTI-ACCUM sequence to correct for cosmic rays and non-linearity. The standard STScI procedure "calnica" version 3.2 was used to reduce the data, which does a bias subtraction, linearity correction, dark subtraction and flat field. A guide-star reacquisition during the 6-orbit program forced the spacecraft orientation angle to change during the observation and 8 of the 48 frames in each filter had to be rotated with respect to the rest. An IDL routine developed by the NICMOS team at the University of Arizona was used to make the mosaic in each filter, and overlapping good pixels were median combined. Bicubic interpolation was used to shift and rotate the images. The effective plate scale is 0.2035”.

The NICMOS H$_2$ image is constructed, in principle, by subtracting an appropriately flux-calibrated F215N mosaic from the F212N mosaic. However, a simple subtraction did not yield a satisfactory line image and additional steps were taken, as described here. The thermal background (as measured in regions devoid of stars due to high extinction)
was removed from the data; DC levels of 0.61 adu/s and 0.71 adu/s were subtracted for F212N and F215N, respectively. Random fluctuations in DC levels by quadrant in the NICMOS detectors contributed to another (much fainter) DC background that needed to be subtracted in rectangular patches; this subtle effect only was apparent in the F212N-F215N difference image and could not be perfectly corrected due to the contamination by the stars that dominate both mosaics. Next, the F215N images were scaled to the F212N image in order to minimize the stellar residuals upon subtraction; the scale factor used was 1.02. Both positive and negative stellar residuals remained, however, due to intrinsic variations in stellar colors (mostly due to patchy extinction) and due to PSF differences in alignment and illumination of the undersampled pixels. In order to remove the high-spatial frequency residuals and to improve the signal/noise, a 5x5 pixel median filter was applied to the difference image, excluding very negative pixels from the median procedure. The resultant spatial resolution obtained after medianing was estimated by measuring the effect of the same median on the continuum image: stars were measured to increase in FWHM from 0.5” to 0.7”. The reduction in flux of individual bright pixels in the H$_2$ image due to the median filter was measured to be not more than a factor of 2.5. The flux in 1” apertures remained constant after applying the median filter. Finally, the difference image was converted to line flux units with the calibration supplied by STScI. Due to the leakage of blueshifted Br gamma emission into the 2.15 µm continuum filter, portions of the “mini-spiral” of ionized gas within the inner parsec show up as negative in the H$_2$ image (masked to zero is equivalent to white in the H$_2$ image). The final NICMOS H$_2$ mosaic is shown in reverse grayscale in Figures 2a-b, 3 and 7 and the features discussed in this paper are labelled in Figure 2b. Registration of the NICMOS data with the radio data was achieved by aligning position of IRS 7, the brightest continuum source in the NICMOS image, with its radio maser position. The position of Sgr A* is taken to be that given in Menten et al. 1997. Alignment accuracy is estimated to be correct to better than 1 NICMOS pixel (0.2”).
Observations of the 2.122 \( \mu m \) line of H\(_2\) were also obtained with the Anglo-Australian Telescope (AAT) in June 1998, using the IRIS 1–2.5\( \mu m \) camera in conjunction with the UNSWIRF\(^1\) Fabry-Perot etalon (Ryder et al. 1998). With a FWHM spectral resolution of \( \sim 75 \) kms\(^{-1}\), a pixel size of 0.77″ and a 100″ circular field of view, the etalon is scanned through a spectral line of interest with a 40 kms\(^{-1}\) plate spacing, and with an ‘off-line’ setting chosen to provide continuum subtraction. Sky frames are also taken for each etalon spacing.

Four positions were observed, F1 to F4, with central positions (17\(^{\text{h}}\) 42\(^{\text{m}}\), -28\(^{\circ}\) (1950)) of (30°, 58’ 45”), (28°, 59’ 40”), (33°, -29° 00’ 10”) & (34.5°, 59’ 50”) respectively. These are shown in Figure 1, overlaid on a K–band (2.15\( \mu \)m) continuum image of the Galactic center from NICMOS. A mosaic of the four frames was carried out using FLATN in AIPS and the grayscale image of integrated line emission is displayed in Figure 2c. 6, 11, 6 & 7 plate spacings were taken at each position, covering 200, 395, 200 & 240 kms\(^{-1}\), respectively. Integration time per frame was 2 minutes. Seeing varied between 2” and 3” during the observations.

Data reduction was through a custom software page using IRAF\(^2\). Frames are linearised, flat-fielded using a dome flat, sky-subtracted, shifted to align the stars in each frame, smoothed and the off-line frame subtracted from each on-line frame (each having been appropriately scaled to minimize residuals from the subtraction process). Stacking the frames yields a data cube, which is then fitted pixel-by-pixel with the instrumental profile (a Lorentzian) to yield a line image. Furthermore, the line center is also determined from the peak position of the fitted line. The data cube obtained is not a true velocity-position cube as the wavelength associated with each pixel (as well as the spectral resolution) varies

\(^{1}\)University of New South Wales InfraRed Fabry-Perot

\(^{2}\)Image Reduction and Analysis Facility (www.iraf.noao.edu)
across the array (by up to 40 km/s), but the variation can be calibrated by observation of an arc line, and hence the line center at each pixel determined. Typically this is accurate to $\sim 10 \, \text{km/s}$, but in the crowded environment of the Galactic center continuum subtraction was imperfect and accuracy varies across the field. Absolute wavelength calibration is then made by comparison to the etalon setting for the H$_2$ emission in known sources, in this case IC 4406 (at $-41 \, \text{km/s}$ $V_{LSR}$) and M17 ($+21 \, \text{km/s}$ $V_{LSR}$). The overall accuracy in the line center determination is estimated to be $\sim 25 \, \text{km/s}$. The moderate spectral resolution, and the wide wings of the instrumental profile, preclude any attempt to determine further spectral information other than the line center. Flux calibration was made by comparison to the star HR 6378 with a K–band magnitude of 2.29 magnitudes, and the absolute accuracy is typically around 30% in the line fluxes. An image was also obtained in the 2.166$\mu$m Br $\gamma$ hydrogen recombination line in June 1999, with a widely-spaced velocity-channel separation of 95 km/s. While a detailed discussion of these results will be given elsewhere, selected images from this data are used in this paper.

3. Results and Discussion

3.1. H$_2$ Gas in the Circumnuclear Ring

The region observed with UNSWIRF is shown in Figure 1, with the four positions marked by circles overlaid on a 2.2$\mu$m NICMOS continuum image of the Galactic center. Figure 2a shows the H$_2$ image obtained with NICMOS, overlaid with the outermost contour from the 88.6 GHz J=1–0 line map of HCN (Güsten et al. 1987), which delineates the extent of dense gas in the CND. The H$_2$ emission is shown in reverse grayscale. Also marked are the positions of OH (1720 MHz) masers (from Yusef-Zadeh et al. 1996) and Sgr A*. Although the median filtering which was applied twice removed many of the stellar residuals due to the undersampled pixels, some artifacts remain. Nevertheless, the overall
spatial distribution of the H\textsubscript{2} emission is clear, and many individual features are clearly resolved. Figures 2b,c present the prominent H\textsubscript{2} features labelled on an NICMOS H\textsubscript{2} image and the mosaic of four UNSWIRF images of H\textsubscript{2} line intensity, respectively. The strongest H\textsubscript{2} emission is associated with the NE and SW lobes of the CND, as first mapped by Gatley et al. (1984, 1986). The peak H\textsubscript{2} intensities in the NE and SW are 7 and 8 × 10\textsuperscript{-15} erg s\textsuperscript{-1} cm\textsuperscript{-2} arcsecond\textsuperscript{-2}, respectively. Apart from the CND, the most striking feature is a linear filament to the NW of the CND. Centered on $\alpha = 17^h42^m28.5^s, \delta = -28^o5830'$, and extending about 1' in a NE-SW direction, the FWHM of the width of the filament is only $\sim 1.3'$ (0.05pc at the distance of 8kpc). Several compact knots of emission can be found along the length of the filament. The most pointlike of these is found at the filament’s SW end and is located 24.8'' W, 28.3'' N of Sgr A*. As there is no detected stellar counterpart in the continuum filter to this compact H\textsubscript{2} knot, it is clearly not an artifact of improper stellar subtraction; therefore it is likely nonstellar in origin despite its pointlike appearance. The typical intensity of the H\textsubscript{2} emission along the linear feature is between $\sim 2 - 3 \times 10^{-15}$ erg s\textsuperscript{-1} cm\textsuperscript{-2} arcsecond\textsuperscript{-2}. There is a gap in the filament near $\alpha = 17^h42^m29^s, \delta = -28^o5830'$.

Contours of radio continuum emission at 6 cm obtained with the Very Large Array of the National Radio Astronomy Observatory\footnote{The National Radio Astronomy Observatory is a facility of the National Science Foundation, operated under a cooperative agreement by Associated Universities, Inc.} (Yusef-Zadeh & Morris 1987; Yusef-Zadeh & Wardle 1993) are superimposed on the NICMOS H\textsubscript{2} emission in Figure 3. The distribution of ionized gas near the N and S lobes is asymmetric and the spiral-shaped structure of Sgr A West is evident near the center of the image. Figure 4 shows the distribution of molecular hydrogen emission overlaid with contours of Br\textgamma emission extracted from the data cube at 125 kms\textsuperscript{-1} and −160 kms\textsuperscript{-1}. As expected, the distribution of Br\textgamma line emission broadly
follows the radio free-free emission, the lowest contour following the edge of the S lobe of the CND in Figure 4b but avoiding the N lobe in Figure 4a. The intensity of Br$\gamma$ emission is stronger in the N than the S lobe by a factor of about 3, peaking at $2 \times 10^{-14}$ erg s$^{-1}$ cm$^{-2}$ arcsecond$^{-2}$, in the N and $6 \times 10^{-15}$ erg s$^{-1}$ cm$^{-2}$ arcsecond$^{-2}$, in the S. The brightest Br$\gamma$ emission arises from the mini-cavity with the flux of $3 \times 10^{-14}$ erg s$^{-1}$ cm$^{-2}$ arcsecond$^{-2}$ (Roberts, Yusef-Zadeh and Goss 1996) which lies near Sgr A*. The emission velocities for the Br$\gamma$ features peak at -350, +29 and -160 for the mini-cavity, N. arm and S. arm of Sgr A West, respectively (A more detailed discussion of Br$\gamma$ data will be given elsewhere).

Figure 5a shows the distribution of the integrated intensity of the H$_2$ 1–0 S(1) line for Field 1 (F1), which includes the northern part of the CND and the newly discovered filament to its NW. Figure 5b shows the same image superimposed on a 2.2$\mu$m continuum image, and also has the line center velocities for the principle emission features labelled, in addition to the OH 1720 MHz masers. The brightest clump in the N lobe, with $V_{LSR}$ velocity of 110-115 kms$^{-1}$, has peak intensity of $6.6 \times 10^{-15}$ erg cm$^{-2}$ s$^{-1}$ arcsec$^{-2}$. The 134 kms$^{-1}$ OH maser (B) lies adjacent to the western edge of the N. lobe.

The H$_2$ linear filament is brightest at $\approx 75$ kms$^{-1}$, but the line center velocity decreases to $\sim 50$ kms$^{-1}$ along its NE extension. The western edge of the CND (sometimes called the western Arc) appears at velocities ranging between 55 and 80 kms$^{-1}$. The OH (1720 MHz) masers in this vicinity are distributed along the edges of the N lobe and the filament where the intensity of H$_2$ emission falls from the peak values, to levels of 1–2 $\times 10^{-15}$ erg cm$^{-2}$ s$^{-1}$ arcsec$^{-2}$. At the position of the 43 kms$^{-1}$ maser (C) a ridge of diffuse H$_2$ emission appears to connect the filament to the western edge of the CND. However, the interpretation at this location is confused by the presence of the “70 kms$^{-1}$ cloud” seen in [OI] 63$\mu$m (Jackson et al. 1993), a feature known to be associated with the CND. The kinematics of the H$_2$ gas in the filament and the ridge, with velocities around 60 kms$^{-1}$,
suggests that the H$_2$ emission from these features is indeed associated with the 70 kms$^{-1}$ cloud.

A plume-like feature within the CND, as shown in Figure 5a, also extends from just northeast of Sgr A* near IRS 7 is located at $\alpha = 17^h42^m30.2^s, \delta = -28^\circ59'3''$. This new feature peaks at emission velocities near 80 kms$^{-1}$ with a peak flux of $1.5 \times 10^{-15}$ erg cm$^{-2}$ s$^{-1}$ arcsec$^{-2}$. It does not appear to be associated with any ionized streamers of Sgr A West but is adjacent to the [OI] 63$\mu$m peak detected by Jackson et al. (1993) at similar velocities.

H$_2$ emission is also present on the negative Galactic longitude side of the CND. The maps in Figures 6a and 6b show the line intensity in Field 2 (F2), centered near the southern lobe of the CND. The brightest clump of the S lobe, with $V_{LSR}$ velocity of $-40$ kms$^{-1}$, has peak intensity of $7.6 \times 10^{-15}$ erg cm$^{-2}$ s$^{-1}$ arcsec$^{-2}$. Weak, diffuse H$_2$ emission is also present outside and inside the CND, with intensities $\sim 1 \times 10^{-15}$ erg cm$^{-2}$ s$^{-1}$ arcsec$^{-2}$. Within the CND, as outlined by the HCN emission (Wright et al. 1989), there is diffuse H$_2$ emission, at positive velocities. Diffuse emission also extends beyond the CND, to the SW, with both negative and positive velocity components. It is clear that there is H$_2$ gas within the molecular cavity and that its kinematics on the negative-longitude side of the CND is inconsistent with the sense of rotation of the circumnuclear ring.

### 3.2. The Nature of H$_2$ Emission from the Circumnuclear Ring

Our UNSWIRF and NICMOS observations detect peak fluxes in the 1-0 S(1) molecular hydrogen line of approximately $7 \times 10^{-15}$ erg s$^{-1}$ cm$^{-2}$ arcsec$^{-2}$ in the N and S lobes. This is comparable to the fluxes reported by Gatley et al. (1986) ($\approx 4 \times 10^{-15}$ erg s$^{-1}$ cm$^{-2}$ arcsec$^{-2}$ in an 18$''$ diameter aperture) but somewhat more than by Burton & Allen (1992).
(≈ 2 × 10^{-15} \text{erg s}^{-1} \text{cm}^{-2} \text{arcsec}^{-2} \text{in a 1}.''4 \text{ by 4}.''7 \text{ EW aperture placed, but not peaked, on the N lobe}). Adopting \( A_K = 3 \), the extinction-corrected line intensity from the lobes is approximately \( 4 \times 10^{-3} \text{erg s}^{-1} \text{cm}^{-2} \text{sr}^{-1} \) at its peak. The extinction, of course, could be higher toward the N. and S. lobes as recently discussed by Stolovy, Scoville & Yusef-Zadeh (2001).

The distribution of emission is broadly consistent with the orientation of the inner circumnuclear disk inferred from HCN observations (Güsten et al. 1987; Jackson et al. 1993): a 0.5 pc thick torus of emission with normal surface intensity \( \sim 10^{-3} \text{erg cm}^{-2} \text{s}^{-1} \text{sr}^{-1} \text{inclined at 70 degrees to the line of sight will produce the N and S lobes by limb brightening. The source of excitation of the H}_2 \text{ emission is puzzling. Gatley et al. (1984) argued that the inner edge of the circumnuclear ring is shocked by a wind from the mass-losing stars in the central few pc, for which } M = \sim 3 \times 10^{-3} M_\odot \text{ yr}^{-1} \text{ and } v_{\text{wind}} \approx 750 \text{ km s}^{-1} \text{ (Krabbe et al. 1991; Najarro et al. 1997). At 1.7 pc, this combined wind would be capable of driving a shock of speed } v_s \text{ into a pre-shock medium of H density } n_H \text{ with } n_H v_s^2 \approx 2 \times 10^6 \text{ cm}^{-3} \text{ km}^2 \text{ s}^{-2}. \) However, the observed intensity can be produced by C-type shock waves with \( v_s \approx 30 \text{km s}^{-1} \) if the pre-shock density is \( \sim 10^4 \text{ cm}^{-3}, \) or in both C- and J-type shocks with \( v_s \approx 20 \text{km s}^{-1} \) if the pre-shock density is \( \gtrsim 10^5 \text{ cm}^{-3} \) (Kwan 1977; Draine, Roberge & Dalgarno 1983; Kaufman & Neufeld 1996a). Thus the ram pressure of the IRS 16 wind is at most one fifth of that required.\(^4\)

The intense UV field \( (G_0 \sim 10^5) \) at the Galactic center (Sternberg & Dalgarno 1989; Burton, Hollenbach & Tielens 1990) is another source of excitation, although UV may be prevented from reaching the eastern side of the ring by intervening material associated

\(^4\)Gatley et al. (1984) conclude that this ram pressure is sufficient, but this is based on an estimate that the \( \sim 50 L_\odot \) emitted in the 1–0 S(1) line arises from \( \sim 0.01 M_\odot \text{ of gas at 2000 K}, \) which appears to be a factor of ten too low.
with the Northern Arm (Genzel, Hollenbach & Townes 1995). In equilibrium, a PDR emits $\sim 10^{-3}$ erg cm$^{-2}$ s$^{-1}$ sr$^{-1}$ in the 1–0 S(1) line only if the gas density $\gtrsim 10^7$ cm$^{-3}$, but then the predicted [OI] 63$\mu$m intensity ($\gtrsim 0.1$ erg cm$^{-2}$ s$^{-1}$ sr$^{-1}$; Burton et al. 1990), is several times higher than observed (Jackson et al. 1993). Although the presence of high-density gas ($n \sim 10^6$–$10^8$ cm$^{-3}$) at the inner edge of the circumnuclear ring has been inferred from HCN observations (Güsten et al. 1987, Jackson et al. 1993, Marshall, Lasenby & Harris 1995), this material has a sky covering fraction $\sim 0.1$, and so the H$\_2$ line intensity would be diluted by this factor. In fact, the observed fluxes in the [OI] 63$\mu$m, [CII] 158$\mu$m and [SiII] 35$\mu$m far–IR lines are consistent with a density $\sim 10^5$ cm$^{-3}$ and covering fraction $\sim 1$ (Burton et al. 1990; Wolfire, Hollenbach & Tielens 1990), consistent with UV heating of the envelopes of the dense cores seen in HCN (Jackson et al. 1993). In equilibrium, the UV-heated envelopes would produce a flux of only $\sim 10^{-5}$ erg cm$^{-2}$ s$^{-1}$ sr$^{-1}$. The H$\_2$ emission from the envelopes is increased substantially if their exposure to the UV flux varies on a timescale $\lesssim 300$ yr (Goldshmidt & Sternberg 1995; Hollenbach & Natta 1995). In this case, the 1–0 S(1) line intensity is $\sim 10^{-3}$ erg cm$^{-2}$ s$^{-1}$ sr$^{-1}$, the 2–1/1–0 S(1) ratio is $\sim 0.1$, and the far-IR line intensities are still matched because they reach equilibrium on a much shorter timescale (Hollenbach & Natta 1995). The only plausible source of variation on this time scale is the shadowing by other clumps that would occur if $f_A \sim 1$ and the clumps have size $\sim 0.01$ pc, assuming that the clump-clump velocity dispersion is $\sim 30$ kms$^{-1}$. A similar shadowing effect has been postulated to produce intense CI fine-structure emission from dense PDRs in molecular clouds (Störzer, Stutzki & Sternberg 1997).

The emission could also arise from gas heated by the dissipation of the $\approx 30$ kms$^{-1}$ velocity dispersion in the ring (e.g. Genzel 1989; Jackson et al. 1993), either by internal shock waves in a homogeneous, but turbulent, medium or by collisions in a clumpy

\footnote{That we can think of.}
medium. The strength of the H$_2$ line emission from clump collisions can be estimated as follows. Characterize the clumps by radius $r$, number density $n = n_6 10^6$ cm$^{-3}$, and clump-to-clump velocity dispersion $v = v_{30} \cdot 30$ km s$^{-1}$. In a collision, assume that a shock of area $\pi r^2$ and speed $v$ is driven into each cloud, and that a fraction $\varepsilon$ of the mechanical energy flux $\frac{1}{2} \rho v^3$ incident on each shock is converted into emission in the 1–0 S(1) line of H$_2$. Using the collision cross section, $\sigma \sim \pi (2r)^2$, and the duration of a collision, $\sim 2r/v$, then the fraction of clumps that are being shocked at any given time is $\approx n_{cl} \sigma v \cdot 2r/v = 8\pi r^3 n_{cl} = 6f_V$, where $n_{cl}$ is the number of clumps per unit volume and $f_V$ is the volume filling fraction of the clumps. The column density along the $\approx 1$ pc intersection of the line of sight with the lobes of the circumnuclear ring inferred from far-IR emission from dust grains is $\approx 10^{22}$ cm$^{-2}$ (Latvakoski et al. 1999). This implies $f_V \approx 0.0032/n_6$, and the line intensity is

$$I = \frac{\varepsilon \rho v^3}{8\pi} 6f_V f_A \approx 1.0 \times 10^{-3} \varepsilon_{0.02} f_A v_{30}^3 \text{erg cm}^{-2} \text{s}^{-1} \text{sr}^{-1}$$

(1)

where $f_A$ is the area covering fraction of the clumps and $\varepsilon = 0.02 \varepsilon_{0.02}$. $\varepsilon$ is an initially increasing function of shock speed and density; dropping sharply for shock speeds in excess of 40–50 km s$^{-1}$ when shocks become J-type (Hollenbach & McKee 1989), and decreasing at densities $\gtrsim 10^8$ cm$^{-3}$ because of collisional de-excitation of H$_2$ (Kaufman & Neufeld 1996b). The maximum value, $\sim 0.02$, is obtained for shock speeds between $\sim 30$ and $\sim 45$ km s$^{-1}$ and $n \sim 10^5$–$10^7$ cm$^{-3}$ (Kaufman & Neufeld 1996a). Thus we conclude that clump collisions are capable of generating the observed intensity provided that $f_A \gtrsim 1$ and $n \gtrsim 10^5$ cm$^{-3}$.

Both the time-dependent UV irradiation and clump collision model produce intensities that are roughly density-independent, which may explain the uniformity of the H$_2$ emission around the ring. Both scenarios also explain why the large-scale distribution of H$_2$ emission from the ring traces the HCN J=1–0 emission reasonably well. The lack of obvious small-scale fluctuations in the H$_2$ emission implies that several UV-irradiated clumps or
colliding clumps must be present per square arcsecond. In the colliding clump scenario, this requires that the clump density \( \gtrsim 10^6 \text{cm}^{-3} \).

An additional process that could complicate the interpretation of H\(_2\) emission from the ring is its physical interaction with Sgr A East evidenced by OH (1720 MHz) masers. The new class of OH (1720 MHz) masers which are also called “supernova masers” are very rare and in all observed 20 sources that have been reported, the masers are physically associated with supernova remnants (Frail et al. 1996; Green et al. 1997; Koralesky et al. 1998; Yusef-Zadeh et al. 1999c). The most obvious SNR candidate associated with OH (1720 MHz) masers in the Galactic center is the nonthermal Sgr A East SNR driving a shock into the CND. Recent analysis of the 1720 MHz maser observations carried out in 1986 shows a -132 kms\(^{-1}\) OH (1720 MHz) maser associated with the S. lobe (Yusef-Zadeh et al. 2001; M. Goss, private communication). These high-velocity masers give a compelling evidence that the masers of the CND are produced by the expansion of Sgr A East and that the H\(_2\) molecular emission in the CND is in part shock excited externally by Sgr A East. In addition, the highly blue and red-shifted OH (1720 MHz) maser features correspond to the systemic velocity of the molecular gas in the CND. This is because the path of maximum amplification for inversion of the 1720 MHz OH maser is formed when the acceleration produced by the shock is transverse to the line of sight (Frail, Goss and Slysh 1994). This implies that the rotational velocity of the circumnuclear ring is about 130 kms\(^{-1}\).

### 3.3. The H\(_2\) Linear Filament

The width of the linear filament from the NICMOS observations is \( \lesssim 1.3'' \), and the H\(_2\) 1–0 S(1) line intensity is \( \approx 1 \times 10^{-4} \text{erg cm}^{-2} \text{s}^{-1} \text{sr}^{-1} \). Several arguments imply that the filament is shock-heated gas rather than from a PDR. Shock models can easily produce the observed intensity and the H\(_2\) emission velocity peaks at 50–75 kms\(^{-1}\) (see Figure 5b),
which suggests that it is associated with OH (1720 MHz) maser C at 43 km s\(^{-1}\). PDR models, on the other hand, require \(G_0 \sim 10^6, n_H \gtrsim 10^6\) cm\(^{-3}\) and a high inclination to the line of sight (e.g. Burton \textit{et al.} 1990). The \(H_2\) emission in a PDR arises in a layer of thickness corresponding to \(A_v \approx 1\), which would be \(\lesssim 2 \times 10^{15}\) cm, corresponding to an angular scale \(\lesssim 0'02\). Further, there is no evidence for the associated ionization front as seen both in high-frequency radio continuum and Br\(\gamma\) line images. Interestingly, the \(H_2\) filament lies along the western edge of the Sgr A East shell (Yusef-Zadeh \textit{et al.} 1999b) which is known to be nonthermal. Figure 7 shows the distribution of \(H_2\) line emission based on NICMOS observations superimposed on a contour of 20 cm emission from the Sgr A East shell. The alignment of the western edge of the nonthermal Sgr A East shell, the linear \(H_2\) filament and maser C is used as a compelling evidence that the \(H_2\) filament and the OH (1720 MHz) maser C are tracing shocked molecular gas produced by the expansion of Sgr A East into the western edge of the 50 km s\(^{-1}\) molecular cloud.

3.4. \(H_2\) Emission and OH (1720 MHz) Masers

Figure 2a shows the large-scale view of \(H_2\) emission from NICMOS observations outlined by contours of HCN emission. A higher concentration of stars to the northeast is likely to be due to the Sgr A East 50 km s\(^{-1}\) cloud absorbing the background stellar continuum. Figure 2 shows a number of \(H_2\) emitting clouds beyond the contours of HCN emission. We describe below individual sources of \(H_2\) emission.

The region near \(\alpha = 17^h42^m32^s, \delta = -29^\circ00'30''\) to the southeast of Figure 2b is of particular interest because a number of OH (1720 MHz) masers have been detected there (Yusef-Zadeh \textit{et al.} 1996). The locations of the OH (1720 MHz) maser features A and D–G (velocities of +50–60 km/s) within the M-0.02-0.07 ("50 km/s") cloud are indicated in this Figure. Spectroscopy toward these sources showed evidence of weak \(H_2\) emission lying close
to the position of these masers (Wardle, Yusef-Zadeh and Geballe 1999). Figure 8 (F3 in Figure 1) shows the integrated H$_2$ 1–0 S(1) emission towards these masers. Similarly, Figure 9 shows the H$_2$ distribution in an overlapping pointing (F4 in Figure 1).

The masers in Figures 8 and 9 appear to be aligned along an elongated nonthermal continuum feature at the southeastern boundary of Sgr A East at 20 cm (Yusef-Zadeh and Morris 1987; Yusef-Zadeh et al. 1996). The H$_2$ gas which appears to be associated with masers A–E (those labelled 66 and 57 kms$^{-1}$) has a flux density 5–10 $\times 10^{-16}$ erg s$^{-1}$ cm$^{-2}$ arcsec$^{-2}$ and a mean velocity of about 95 kms$^{-1}$. NH$_3$ emission between −41 and 101 kms$^{-1}$ (Coil and Ho 1999) also lies adjacent to the maser sources, but is not seen associated with the NS elongated H$_2$ feature centered at $\alpha = 17^h42^m32.7^s, \delta = -28^059'45''$. The G OH (1720 MHz) maser (labelled by 55 kms$^{-1}$) does not appear to have any detectable H$_2$ counterpart. While the velocities of the OH masers and the corresponding H$_2$ emission are not the same, differing by $\sim 30$ kms$^{-1}$ (as is the case for the OH masers in the northern lobe of the CND), they do support a physical association between them. The poor spatial correlation between OH masers and NH$_3$ gas is probably explained by the restricted physical conditions under which OH (1720 MHz) masers can be formed (Lockett et al. 1999) as well as the fact that the velocities of OH (1720 MHz) masers trace the systemic motion of the molecular clouds. A number of high-velocity H$_2$ features are also noted lying within and at the boundary of the Sgr A East shell (centered at $\alpha = 17^h42^m32.7^s, \delta = -28^059'35''$ and $\alpha = 17^h42^m37^s, \delta = -28^059'50'.)$ These are best shown in Figure 9 and have line center velocities ranging between 85 and 140 kms$^{-1}$.

Two prominent H$_2$ clouds are also noted in projection against the interior of the Sgr A East shell and to the north of the N. lobe near $\alpha = 17^h42^m33^s, \delta = -28^058'15''$. These features which are noted in Figures 2a,b, 7 are located about 90'' NE of Sgr A* and are labelled as ”Outer H$_2$ Clumps” in Figure 2b,. The 20cm image of this field
shows a nonthermal ridge of emission at this location. The morphology of this ridge with respect to the distribution of the CND was recently discussed (see the supplement figure of Yusef-Zadeh, Melia and Wardle 2000) as possible evidence for the physical interaction of the CND and Sgr A East. The velocity structure of these H$_2$ clouds are unknown, lying outside the UNSWIRF fields, thus their physical association with either Sgr A East or the CND is unclear.

3.5. The Outer H$_2$ Filament and Clumps

Another new straight filamentary structure which appears somewhat broader and weaker than the linear filament is shown in Figures 2a,b. The typical H$_2$ flux uncorrected for extinction ranges between 0.7 and $1.7 \times 10^{-15}$ erg s$^{-1}$ cm$^{-2}$ arcsecond$^{-2}$. This feature is oriented roughly in the N-S direction and extending well beyond the inner edge of the CND. This ”Outer Filament” is seen to extend for at least 50″ (and in fact may extend beyond the boundary of the NICMOS image). This straight but clumpy Outer Filament is of order 2-3″ in FWHM across and is coincident with a similarly elongated structure observed in the 34.8μm [SiII] line (Stolovy 1997). An enhancement in the [SiII]/dust continuum in this region also suggests an increase in the atomic silicon abundance due to grain destruction by shocks. In addition, number of H$_2$ clumps are seen throughout this region, two of which located 50″ E and 70″ N of Sgr A*. The ”Outer H$_2$ Clumps” to the NE of the northern lobe appear to be located between the inner edge of the nonthermal shell of Sgr A East and the outer edge of the CND.
3.6. Extinction Clouds

The prominent H\textsubscript{2} filament as well as the N lobe and the western edge of the CND are clearly visible, in black. A number of extinction clouds are apparent throughout the image (evident in white in the figure). Areas of high extinction are apparent in the continuum image (Fig. 1) as regions in white, marking a relative absence of stars, and in the H\textsubscript{2} line image (Fig 2b, also in white) as regions where the residuals from imperfect continuum subtraction are least, a result of there being less stars there in the first place. Because the stellar flux is weak in its surface brightness at both the 2.12\,\mu m and 2.15\,\mu m images, the areas of high extinction show up flatly near zero in the H\textsubscript{2} image, which appears as white patches in the reverse grayscale. We discuss below the association of two prominent extinction clouds with Sgr A East and Sgr A West.

3.6.1. N. Arm Extinction Cloud

An extinction feature in the NICMOS H\textsubscript{2} image, with an angular size of about 20\arcsec, coincides with the gap in the CND near \( \alpha = 17^h 42^m 30^s, \delta = -28^\circ 58' 50'' \) or about 30\arcsec N of Sgr A\textsuperscript{*} (cf. Figures 2a,b & 7). Several factors suggest that this cloud is associated with the Northern Arm. The northernmost tip of the N arm in the 6 cm data, near IRS8, as seen in Figure 3, coincides with the cloud. The kinematics of ionized gas along the N arm show multiple non-circular velocity components at \( \alpha = 17^h 42^m 29.8^s, \delta = -28^\circ 59' 00'' \), where the N arm bends in an otherwise continuous velocity distribution (Serabyn and Lacy 1985). Stolovy, Scoville, and Yusef-Zadeh (2000) have recently measured the extinction toward this cloud at subarcsecond resolution to be at least \( A_v \sim 60 \) magnitudes. It is likely higher than this in the darkest parts beyond the sensitivity of the measurement. In addition, the northern half of the N arm also shows a sudden drop by a factor of 2 in its surface brightness at 6 cm and a dearth of [FeII] 1.64\,\mu m emission (Yusef-Zadeh et al. 1999a) to the
north of $\alpha = 17^h 42^m 29.7^s, \delta = -28^\circ 50' 00''$—ie where the extinction feature is (Yusef-Zadeh and Wardle 1993). However, the strongest evidence that the extinction cloud lies within the CND comes from the $\lambda 1.2$ cm VLA continuum image shown in Figure 10. This shows the N Arm of Sgr A West and a faint semi-circular shell of ionized gas surrounding the northern tip of the N arm. Similarly, a radiograph of this region (see Fig. 4 of Yusef-Zadeh & Morris 1987), reveals what appears to be a limb-brightened hole in the distribution of continuum emission at this location. The morphology in Figure 10 is suggestive of a neutral cloud surrounded by ionized gas (Yusef-Zadeh, Zhao & Goss 1994). The ionized shell suggests that the cloud is photoionized externally and is associated with the northern tip of the N arm. Indeed, this feature coincides with the outer rim of the extinction cloud seen with NICMOS at 2.12$\mu$m. Its surface brightness at 1.2 cm, $\sim 0.2$ mJy within a 0.3'' $\times$ 0.2'' beam, is at the level expected for the ionizing radiation field within the cavity. This cloud is possibly the single cloud from which the N arm originated before falling on a circular orbit toward Sgr A*. Earlier kinematic studies of 12.8$\mu$m [NeII] line emission by Serabyn and Lacy (1985) predicted such a cloud would be colliding with the CND. The cloud has also been detected in an HI absorption study of this region, where it appears as a feature at 130 kms$^{-1}$ (Plante, Lo & Crutcher 1995). The position, strength and direction of HI Zeeman splitting measurements at +130 kms$^{-1}$ agree with the Zeeman study of the 1720 MHz OH masers at the same location (Plante et al. 1995, Yusef-Zadeh et al. 1996).

3.6.2. The Extended Extinction Cloud

Another prominent and extended extinction feature is located to the NW of the Linear H$_2$ Filament, extending NE-SW from around $\alpha = 17^h 42^m 27^s, \delta = -28^\circ 58' 15''$ or about 70'' NW of Sgr A* in Figure 2a,b and 7. The boundaries of this feature are not well-defined, but it appears to “wrap around” the linear filament and continue southward, connecting to
the Northern Arm extinction Cloud described in the previous sub-section. The contour of 20cm emission in Figure 7 runs parallel to the inner edge of this extinction feature.

The eastern side of Sgr A East is known to be interacting with the 50 kms$^{-1}$ cloud (e.g. Mezger et al. 1989; Zylka et al. 1990; Serabyn et al. 1992; Yusef-Zadeh et al. 1996; Coil & Ho 1999). However, the interaction of the western half of Sgr A East has not been examined in detail before. The extended extinction cloud discussed here may also be associated with the well-known 50 kms$^{-1}$ cloud, assuming that the OH (1720 MHz) maser at 43 kms$^{-1}$ represents the systemic motion of the cloud at its interaction site with Sgr A East.

A number of weakly emitting radio continuum features, known as the streamers, have also been recognized running perpendicular to the CND (Yusef-Zadeh & Morris 1987; Yusef-Zadeh & Wardle 1993). H110α observations also indicate gas velocities up to +144 kms$^{-1}$ near $\alpha = 17^{h}42^{m}28^{s}, \delta = -28^{0}58^{15^{''}}$ (just to the NW of the H$_2$ filament). Along with the kinematics of the ionized gas near the 43 kms$^{-1}$ OH maser, these velocities are inconsistent with circular orbital motion about the Galactic nucleus. (Yusef-Zadeh, Zhao & Goss 1994). This suggests that these features in the ionized gas are also associated with the same molecular cloud producing the extinction feature at 2.12$\mu$m.

4. Conclusions

In summary, we have presented H$_2$ 1–0 S(1) line observations of the circumnuclear ring and Sgr A East using NICMOS on the HST and UNSWIRF on the AAT. These high spatial and spectral resolution images are correlated with OH (1720 MHz) masers as well as Br $\gamma$ line and radio continuum observations of the complex region of the Galactic center. In spite of the difficulty of detecting shocked molecular gas due to the large intrinsic linewidth of Galactic center molecular clouds, these observations show strong evidence of hot shocked
H$_2$ gas and cool postshock gas as traced by OH (1720 MHz) masers. The interaction of two dynamically coupled systems associated with Sgr A East and the circumnuclear ring is discussed. This argument is based on the fact that in all 20 supernova masers that have been discovered in the Galaxy, OH (1720 MHz) masers are clearly evident at the boundary of supernova remnants and molecular clouds where the interaction is taking place. In the Galactic center region, the expansion of the nonthermal shell of Sgr A East drives a shock into both the 50 km s$^{-1}$ cloud and the circumnuclear ring and produces the observed OH (1720 MHz) masers. Lastly, it was argued that the molecular H$_2$ emission from the circumnuclear ring results from gas heated in the dissipation of the random motion of molecular clumps in the ring.
REFERENCES

Allen, D.A., Hyland, A.R., & Hillier, D.J. 1990, MNRAS, 244, 706
Baganoff, F.K. et al. 2001, in press
Burton, M. & Allen, D.A. 1992, Proc. Astr. Soc. Australia, 10, 55
Burton, M. & Allen, D. 1993, in Astronomical Infrared Spectroscopy: Future Observational Directions, ed. S. Kwok (San Francisco: ASP), 289
Burton, M. G., Hollenbach, D. J. & Tielens, A. G. G. M. 1990, ApJ, 365, 620
Coil, A. & Ho, P.T.P. 1999, ApJ, 513, 752
Draine, B. T., Roberge, W. G. & Dalgarno, A. 1983, ApJ, 264, 485
Eckart, A. & Genzel, R. 1996, Nature, 383, 415
Frail, D.A., Goss, W.M. & Slysh, V.I. 1994, ApJ, 424, L111
Frail, D.A. & Mitchell, G.F. 1998, ApJ, 508, 690
Gatley, I., Beattie, D. H., Lee, T. J., Jones, T. J. & Hyland, A. R. 1984, MNRAS, 210, 565
Gatley, I., Jones, T.J., Hyland, A.R., Wade, R., Geballe, T.R. & Krisciunas, K. 1986, MNRAS, 222, 299
Geballe, T. R., Krisciunas, K., Bailey, J. A. & Wade, R. 1991, ApJ, 370, L73
Genzel, R. 1989, in Proceedings of the 136th Symposium of the International Astronomical Union, Eds: Mark Morris. Kluwer Academic Publishers, Dordrecht, p.393
Genzel, R., Hollenbach, D. & Townes, C. H. 1995, Reports on Progress in Physics, 57, 417
Ghez, A., Klein, B.L., Morris, M. & Becklin, E.E. 1998, ApJ, 509, 678
Güsten, R., Genzel, R., Wright, M. C. H., Jaffe, D. T., Stutzki, J. & Harris, A. I. 1987, ApJ, 318, 124
Goldshmidt, O. & Sternberg, A. 1995, ApJ, 439, 256
Green A.J., Frail, D.A., Goss, W.M. & Otrupcek, R. 1997, AJ, 114, 2058
Hall, D. N. B., Kleinmann, S. G. & Scoville, N. Z. 1982, ApJ, 262, L53
Hollenbach, D. J. & McKee, C. F. 1989, ApJ, 342, 306
Hollenbach, D. & Natta, A. 1995, ApJ, 455, 133
Jackson, J. M., Geis, N., Genzel, R., Harris, A. I., Madden, S., Poglitsch, A., Stacey, G. J. & Townes, C. H. 1993, ApJ, 402, 173
Kaufman, M. J. & Neufeld, D. A. 1996a, ApJ, 456, 611
Kaufman, M. J. & Neufeld, D. A. 1996b, ApJ, 456, 250
Koralesky, B., Frail, D.A., Goss, W.M., Claussen, M.J. & Green, A.J. 1998, AJ, 116, 1323
Krabbe, A., Genzel, R., Drapatz, S. & Rotaciuc, V. 1991, ApJ, 382, L19
Kwan, J. 1977, ApJ, 216, 713
Latvakoski, H.M., Stacey, G.J., Gull, G.E. & Hayward, T.L. 1999, ApJ, 511, 761
Lockett, P., Gauthier, E. & Elitzur, M. 1999, ApJ, 511, 235
Maeda, Y. et al. 2001, in press
Marr, J. M., Wright, M. C. H. & Backer, D. C. 1993, ApJ, 411, 667
Marshall, J., Lasenby, A. N. & Harris, A. I. 1995, MNRAS, 277, 594
Menten, K., Reid, M., Eckart, A. & Genzel, R. 1997, ApJ, 475, L111
Mezger, P.G., Zylka, R. Salter, C.J., Wink, J.E., Chini, R., Kreysa E., 1989, A.A., 209, 337
Najarro, F., Krabbe, A., Genzel, R., Lutz, D., Kudritzki, R. P. & Hillier, D. J. 1997, A&A, 325, 700
Pak, S., Jaffe, D.T. & Keller, L.D. 1996, ApJ, 457, L43
Plante, R.L., Lo, K.Y. & Crutcher, R.M. 1995, ApJ, 445, L113

Ramsay-Howat, S., Mountain, M., Geballe, T.R. 1993 in Astronomical Infrared Spectroscopy. Future Observational Directions, Editor: S. Kwok; Publisher; ASP, Vol. 41; San Francisco, 3

Roberts, D.A. & Goss, W.M. 1993, ApJS, 86, 133

Roberts, D.A. Yusef-Zadeh, F. & Goss, W.M. 1996, ApJ, 459, 627

Ryder, S.D., Sun, Y-S., Ashley, M.C.B., Burton, M.G., Allen, L.E. & Storey, J.W.V. 1998, MNRAS, 294, 338

Serabyn, E. & Lacy, J.H. 1985, ApJ, 293, 445

Serabyn, E., Lacy, J.H. & Achtermann, J.M. 1992, ApJ, 395, 166

Sternberg, A. & Dalgarno, A. 1989, ApJ, 338, 197

Störzer, H., Stutzki, J. & Sternberg, A. 1997, A&A, 323, L13

Stolovy, S. R., Scoville, N. & Yusef-Zadeh, F., PASP, The Fourth Tetons Conference held June 2000 (in press)

Stolovy, S.R. 1997, PhD Thesis, Cornell University

Telesco, C. M., Davidson, J. A. & Werner, M. W. 1996, ApJ, 456, 541

Wardle, M. 1999, ApJ, 525, L101

Wardle, M., Yusef-Zadeh, F. & Geballe, T.R. 1999, in The Central Parsecs, eds. Falcke, et al. 1999, p432

Wolfire, M. G., Tielens, A. G. G. M. & Hollenbach, D. 1990, ApJ, 358, 116

(20) Wright, M.C.H., Genzel, R., Güsten, R. &Jaffe, D.T. 1987, in The Galactic Center, ed., DC Backer, 133, New York: AIP, p133
Yusef-Zadeh, F., Roberts, D.A., Bower, G. & Wardle, M. 2001, in the IAU Symp. 206 on Cosmic Masers, PASP Conference, ed: V. Migenes, in press

Yusef-Zadeh, F. & Morris, M. 1987, ApJ, 322, 721

Yusef-Zadeh, F., Roberts, D.A., Goss, W.M., Frail, D. & Green, A. 1996, ApJ, 466, L25

Yusef-Zadeh, F., Roberts, D.A., Goss, W.M., Frail, D. & Green, A.J. 1999a, ApJ, 512, 530

Yusef-Zadeh, F., Goss, W.M., Roberts, D.A., Robinson, B. & Frail, D. 1999c, ApJ, 512, 230

Yusef-Zadeh, F., Stolovy, S., Wardle, M., Melia, F., Roberts, D., Kassim, N. & Lazio J. 1999b, in The Central Parsecs, eds. H. Falcke et al. ASP series. p197

Yusef-Zadeh, F. & Wardle, M. 1993, ApJ, 405, 584

Yusef-Zadeh, F., Melia, F. & Wardle, M. 2000, Science, 287, 95

Yusef-Zadeh, F., Zhao, J.H. & Goss, W.M. 1995, ApJ, 442, 646

Zylka, R., Mezger, P.G., & Wink, J.E. 1990, AA, 234, 133

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Fig. 1.— 2.15\(\mu\)m continuum image of the Galactic center (from NICMOS observations) overlaid with the four fields (F1 to F4) observed in \(H_2\) using the AAT/UNSWIRF. The circles mark the center of the 100'' diameter frames. The Galactic plane is apparent running NE–SW across the image. Offsets in arcseconds for circular field centers from Sgr A* are: F1 (9.0, 33.3), F2 (-17.2, -21.7), F3 (48.4, -51.7), and F4 (68.3, -31.7). The grayscale in the image ranges from -5 \(\mu\)Jy pixel\(^{-1}\) to 500 \(\mu\)Jy/pixel. The noise level is 1.5 \(\mu\)Jy pixel\(^{-1}\), and the peak pixel at IRS7 (which is NOT saturated) is at at level of 0.12 Jy pixel\(^{-1}\). The flux of IRS7 at 2.15 microns is measured to be 0.95 Jy, or 7.2 mag. Stars as faint as 15th magnitude are measured in uncrowded regions of high extinction. The white cross coincides with the position of Sgr A*.
Fig. 2.— (a) Continuum-subtracted H$_2$ 1–0 S(1) line 2.12µm image of the Galactic center obtained with HST/NICMOS. Contours indicate the extent of the HCN J=1–0 line 88.6 GHz emission from the inner region of the circumnuclear ring, as mapped by Güsten et al. (1987). The star sign coincides with the position of Sgr A*. Despite the high spatial resolution of the HST image, and the stability of the point spread function, this image illustrates the extreme difficulty in obtaining a line image in a crowded region when only low (1%) spectral resolution is used. The H$_2$ emission is shown in reverse grayscale. The star sign corresponds with the position of Sgr A*. (b) Prominent features are labelled on this NICMOS image of H$_2$ line emission. The reverse grayscale ranges from -0.05 to 1.5 ×10$^{-16}$ erg cm$^{-2}$ s$^{-1}$ pixel$^{-1}$ (1 pixel =0.2035″), and is chosen to highlight the fainter features. The noise level is of order 0.02 ×10$^{-16}$ erg cm$^{-2}$ s$^{-1}$ pixel$^{-1}$ and the brightest clumps peak at 3.8 in these units, yielding a peak S/N of 190. The plus signs show the positions of the 134 and 43 kms$^{-1}$ OH (1720MHz) maser B and C, respectively, from Yusef-Zadeh et al. (1996) as well as the -132 kms$^{-1}$ maser feature in the S. lobe (Yusef-Zadeh et al. 2001). (c) Mosaic image of four UNSWIRF frames (F1 to F4) showing grayscale and contours of integrated H$_2$ S(1) 1–0 line emission. The square in the the ring is due to artifacts of mosicing. (In subsequent figures plus signs mark the position of OH (1720 MHz) masers.)

Fig. 3.— Contours of 6 cm radio continuum emission from Sgr A West, obtained with a resolution of 3.4″ × 2.9″ and set at (75, 100, 150, 200, 250, 300, 400, 500) × 1 mJy, superimposed on a greyscale NICMOS image of the H$_2$ 1–0 S(1) line emission from the CND. The star sign corresponds with the position of Sgr A*. 
Fig. 4.— *Greyscale:* The left and right panels show H$_2$ 1–0 S(1) emission from the N and S lobes, in reverse grey scale, extracted from two frames of the UNSWIRF data cubes (F1 at 125 kms$^{-1}$ (N. lobe) and F2 at −85 kms$^{-1}$ (S. lobe), for the two lobes of the circumnuclear ring, respectively). The location of frames F1 and F2 can be seen in Figure 1. *Contours:* Br γ emission extracted from the data cube at 125 kms$^{-1}$ superimposed on the left panel whereas the −160 kms$^{-1}$ Br γ emission is superimposed on the right panel. As discussed in the text, these are not true velocity channel frames, but do give an indication of the morphology of the line emission at these velocities. Contour levels are (1, 2, 3, 4, 5, 7, 9, 22, 25, 20, 30 and 40) times 5×10$^{-16}$ erg s$^{-1}$ cm$^{-2}$ arcsec$^{-2}$. Plus signs mark the location of compact OH (1720) masers (source B from Yusef-Zadeh et al. 1996) associated with the N lobe, emitting at 134 kms$^{-1}$, V$_{LSR}$. The star sign coincides with the position of Sgr A$^*$.  

Fig. 5.— (a) Contours of the integrated 2.12µm H$_2$ 1–0 S(1) line emission from UNSWIRF Field 1 of Figure 1, showing the northern portion of the CND. Contours are overlaid on a greyscale representation of the same data. Contour levels start at, and are in increments of, 5×10$^{-16}$ erg s$^{-1}$ cm$^{-2}$ arcsec$^{-2}$. (b) As for (a) except that the contours are overlaid on a 2.2µm continuum image of the region. Labelled, around the edges of the image, are the line center velocities in kms$^{-1}$ (V$_{LSR}$) of prominent features. Also indicated with plus signs are the location of OH 1720 MHz masers, labelled with their associated emission velocity, and with a cross the location of Sgr A$^*$. The brightest 2µm source, IRS 7, lies 5” to the N of Sgr A$^*$. The central velocities of emission features are labelled to the nearest 5 kms$^{-1}$. The plus signs show the position of OH masers.  

Fig. 6.— As for Figure 5, for UNSWIRF Field 2 of Figure 1, the southern portion of the CND.
Fig. 7.— A contour of 20 cm continuum emission outlining the Sgr A East shell, shown at 0.75 mJy/pixel, pixel scale 0.5″ and resolution 3.1″ × 1.6″, is superimposed on the grayscale continuum-subtracted NICMOS image of the 2.12μm H₂ 1-0 S(1) line emission from the CND and Sgr A East. The plus sign coincides with the position of maser source C from Yusef-Zadeh et al. (1996) and the cross sign coincides with the position of Sgr A*.

Fig. 8.— As for Figure 5b, for UNSWIRF Field 3 of Figure 1, to the SE of the CND.

Fig. 9.— As for Figure 5b, for UNSWIRF Field 4 of Figure 1, to the E of the CND.

Fig. 10.— A greyscale distribution of the ionized gas emitting in the continuum at 1.2 cm, obtained with the VLA at a resolution of 0.3″ × 0.2″, showing the Northern arm of the Sgr A West together with a shell of weak ionized gas around its northern tip. In contract to all other grayscale images shown in this paper, this figure shows a positive grayscale as the continuum emission is seen in white. The arrows are drawn to indicate the region of interest.
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