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H_2 EMISSION FROM THE INNER 400 PARSECS OF THE GALAXY

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ABSTRACT

We have mapped the H_2 $v = 1 \rightarrow 0$ $S(1)$ ($\lambda = 2.1215$ μm) emission line along a 400 pc–long strip and in a 50 pc region in the Galactic center. There is H_2 emission throughout the surveyed region. The typical dereddened ($A_K = 2.5$ mag) H_2 $v = 1 \rightarrow 0$ $S(1)$ surface brightness, $\sim 3 \times 10^{-5}$ ergs s^{-1} cm^{-2} sr^{-1}, is similar to the surface brightness in large-scale photon-dominated regions in the Galactic disk. We investigate two possible excitation mechanisms for the H_2 emission, UV excitation by photons from OB stars and shock waves, and conclude that UV excitation is more likely. The total H_2 $v = 1 \rightarrow 0$ $S(1)$ luminosity in the inner 400 pc region of the Galaxy is 8000 $L_\odot$. The ratio of the H_2 to far-IR luminosity in the inner 400 pc of the Galaxy agrees with that in starburst galaxies and ultraluminous IR-bright galaxies.

Subject headings: galaxies: ISM — infrared: ISM: lines and bands — ISM: molecules

1. INTRODUCTION

Physical conditions in the interstellar medium of the Galactic center[1] are significantly different from those in the solar neighborhood. The thin disk of interstellar material in the Galactic center (size: 450 pc × 40 pc) contains $\sim 10^8$ $M_\odot$ of dense molecular gas, ~10% of the Galaxy's molecular mass (Güsten 1989). The molecular clouds in the Galactic center have higher density, metallicity, and internal velocity dispersion than the clouds in the solar neighborhood (Blitz et al. 1993). Strong radio continuum radiation from giant H II regions and extended low-density (ELD) H II (Sofue 1985), as well as far-IR radiation from dust (Odenwald & Fazio 1984), indicate that the UV radiation field is intense. The energetic conditions in the Galactic center can provide a unique view of the interaction between stellar UV radiation and molecular clouds and a nearby example for the nuclei of other galaxies.

Ro-vibrational lines of H_2 trace photon-dominated regions (PDRs), where far-UV photons excite the H_2, and shocked regions, where the H_2 is thermally excited. As a result, the central regions (~1 kpc) in starburst galaxies are powerful emitters of near-IR H_2 emission (Puxley, Hawarden, & Mountain 1989; Joseph 1989; Lester et al. 1990; Moorwood & Oliva 1990). Vigorous star formation in these galaxies produces large numbers of UV photons, which can excite H_2, while subsequent supernovas can shock-excite the H_2.

Gatley et al. (1984, 1986) and Gatley & Merrill (1993) have observed H_2 emission from the inner 5 pc diameter (2′) in the Galactic center, a much smaller region than those observed in starburst galaxies. With the University of Texas Near-Infrared Fabry-Perot Spectrometer (Luhman et al. 1995), it is now possible to observe H_2 emission over much larger angular scales. We describe here a program to map the Galactic center in H_2 emission on a scale of several degrees (several hundred parsecs) and discuss the likely H_2 excitation mechanism. We can then compare the central region of our Galaxy with those in other galaxies.

[1] We use here the term "Galactic center" to denote the inner several-hundred-parsec region of our Galaxy. We adopt a distance of 8.5 kpc, at which 1° corresponds to 148 pc.

2. OBSERVATIONS

We observed the H_2 $v = 1 \rightarrow 0$ $S(1)$ ($\lambda = 2.1215$ μm) line at the McDonald Observatory 0.91 m telescope in 1994 May and June, using the University of Texas Near-Infrared Fabry-Perot Spectrometer (Luhman et al. 1995). To select a single order from the Fabry-Perot interferometer, we used a 1% interference filter cooled to 77 K. The telescope (f-ratio 13.5), a collimator (effective focal length 343 mm), and a field lens (effective focal length 20 mm) combined to produce a beam diameter of 3.′3 (equivalent disk).

The Fabry-Perot interferometer operated in 92d order with an effective finesse of 17.7, yielding a spectral resolution (FWHM) of 184 km s^{-1}. The scanning spectral range was ±335 km s^{-1} centered at $V_{LSR} = 0$, with 20 sequentially exposed channels. We nodded the telescope between the object and the sky every ~60 s to subtract background and the telluric OH line emission. The sky positions were offset by ±1° in declination ($\Delta l = \pm 0.°85$, $\Delta b = \pm 0.°53$) from the object positions. The telescope pointing error was ±15″. We made a strip map along the Galactic plane running across Sgr A*, at $b = -0.°05$, from $l = -1.°2$ (178 pc) to $+1.°6$ (237 pc), taking spectra at 0.°1 or 0.°2 intervals (Fig. 1). We also mapped the central 50 pc region including Sgr A and the radio "arc" (the arched filaments and the vertical filaments, Yusef-Zadeh, Morris, & Chance 1984) on a 0.°05 grid (see Fig. 2). The relative flux calibration is accurate to ±15%.

3. RESULTS

There is H_2 emission throughout the 400 pc diameter region around the Galactic center. About 70% of the observed positions along the strip at $l = -0.°05$ have detections of the H_2 $v = 1 \rightarrow 0$ $S(1)$ line with a significance of 3 σ or more. Figure 1 shows the intensity distribution of H_2 $v = 1 \rightarrow 0$ $S(1)$ along the strip. The H_2 intensity peaks strongly at Sgr A and decreases continuously from $l = -0.°1$ to $l = -0.°7$. The "dust ridge" seen in 800 μm continuum emission (Lis & Carlstrom 1994) may cause the dip between $l = +0.°1$ and $l = +0.°3$. Away from the nucleus, the intensity distribution is fairly flat.

Figure 2 shows the H_2 $v = 1 \rightarrow 0$ $S(1)$ intensity distribution in the inner 50 pc of the Galaxy overlayed on a simplified radio continuum map (based on Yusef-Zadeh et al. 1984). We have

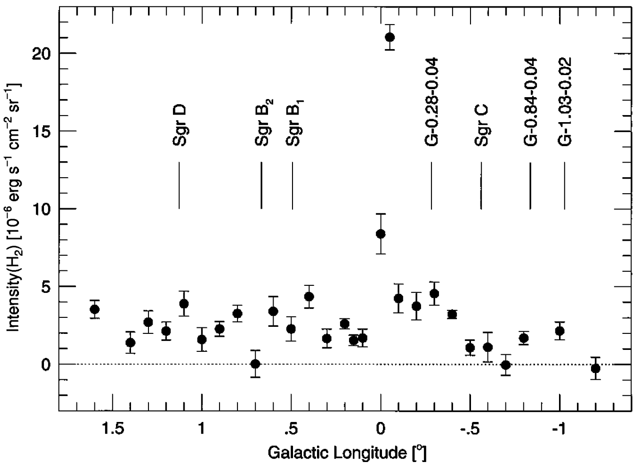

FIG. 1.—Observed intensity distribution of H_2 $v = 1 \rightarrow 0$ $S(1)$ ($\lambda = 2.1215$ μm) along the Galactic plane at $b = -0.05°$. The intensity values have not been corrected for interstellar extinction. The error bars represent 1 σ measurement uncertainties. The strongest emission, at $l = -0.05°$, is from Sgr A. The vertical lines show the positions of the prominent radio continuum sources (Altenhoff et al. 1978).

detected H_2 emission in the arched filaments and in the Sickle at levels comparable to those of the H_2 emission elsewhere along the plane. The inset in Figure 2 shows the $v = 1 \rightarrow 0$ $S(1)$ distribution in the $0.022° \times 0.038°$ region around Sgr A West mapped by Gatley et al. (1986). In Gatley's work, the H_2 appears to be brightest along the inner edge of the circumnuclear gas ring at radius of 1.0–2.5 pc. Our measured flux at ($l = -0.05°$, $b = -0.05°$), 1.5×10^{-11} ergs s^{-1} cm^{-2}, agrees within the errors with the total flux from the map of Gatley et al. (1986; $F = 2.0 \times 10^{-11}$ ergs s^{-1} cm^{-2}). The H_2 emission observed adjacent to ($l = -0.05°$, $b = -0.05°$) most likely

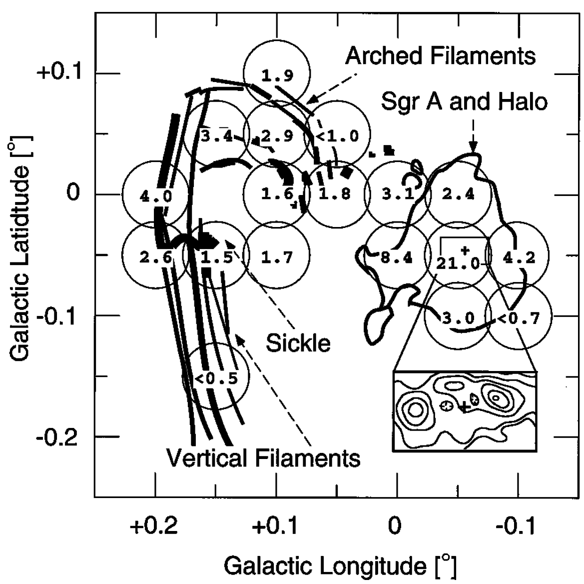

FIG. 2.—Positions (circles with a diameter of the telescope beam size, 3.3′) and measured H_2 intensities (numbers inside the circles in units of 10^{-6} ergs s^{-1} cm^{-2} sr^{-1}) observed in H_2 $v = 1 \rightarrow 0$ $S(1)$ in the inner 50 pc of the Galaxy. Typical measurement uncertainties are 0.7×10^{-6} ergs s^{-1} cm^{-2} sr^{-1}. The heavy lines show a schematic version of the radio continuum distribution (Yusef-Zadeh et al. 1984). The small box and inset show the H_2 $v = 1 \rightarrow 0$ $S(1)$ distribution in the circumnuclear gas ring (Gatley et al. 1986). The plus sign marks the position of Sgr A* ($l = -0.0558°$, $b = -0.0462°$).

arises from portions of the circumnuclear ring beyond their map.

4. DISCUSSION

4.1. *Extinction Correction*

At 2.2 μm, the emission from the Galactic center is attenuated by interstellar material in the foreground ("foreground extinction," mostly 4–8 kpc from the Galactic center) and by material in the Galactic center itself ("Galactic center extinction"). Catchpole, Whitelock, & Glass (1990) mapped the extinction toward the Galactic center by observing the near-IR reddening of giant stars in the central few hundred parsecs. Along our H_2 strip at $b = -0.05°$ (for $-0.6° < l < +0.6°$), the extinction is fairly uniform, with a value $A_K \sim 2.5$ mag. Although most of this extinction is in the foreground, some of it could occur within the Galactic center since Catchpole et al. (1990) were able to identify patches in their maps with $A_K > 2.5$ mag with known molecular clouds in the Galactic center (see Plate 4 in Glass, Catchpole, & Whitelock 1987). Based on this work, we adopt $A_K = 2.5$ mag for the foreground extinction.

The Galactic center extinction greatly exceeds the foreground extinction. Typical ^{12}CO $J = 1 \rightarrow 0$ line strengths along the strip we have surveyed in H_2 are 1500 K km s^{-1} (Oort 1977). This line strength implies an A_K of 10–40 mag, depending on the CO/H_2 and A_K/H_2 ratios in the Galactic center (Sodroski et al. 1994). The extinction through individual clouds may also be substantial ($A_K \sim 10$–30 for a 10 pc–long cloud with $n_{H_2} = 10^4$ cm^{-3}). The relevance of the Galactic center extinction depends on the source of the H_2 emission. Any H_2 emission that originates within the clouds will be highly extincted. If the H_2 emission arises on the cloud surfaces, however, we only miss the H_2 flux from the back side of each cloud.

Clouds that lie in front of other clouds will further reduce the flux that reaches us from the front surfaces. If, in the Galactic center, the velocity-integrated area-filling factor of clouds, f, is substantially greater than unity, extinction by overlapping clouds will reduce the H_2 flux observed from the front surfaces by a factor of $\sim 1/f$ in addition to the foreground extinction and to the loss of emission on the opposite sides of the clouds. Typical clouds in the Galactic center disk have kinetic temperatures of $\sim$70 K and line widths of $\sim$20 km s^{-1} (Güsten 1989). An ensemble of such clouds could produce the observed ^{12}CO $J = 1 \rightarrow 0$ lines in the Galactic center with $f \sim 1$. We therefore conclude that the extinction of any H_2 emission from cloud surfaces facing the Sun beyond the foreground extinction of $A_K = 2.5$ mag discussed above is not substantial. Since the extinction of emission from within the clouds or from the sides facing away from us is difficult to estimate and since no correction is usually made for such effects in giant molecular clouds and galactic nuclei, we make no additional extinction corrections here.

4.2. *UV Excitation of* H_2

If one ignores the region immediately around Sgr A*, the dereddened ($A_K = 2.5$ mag; see § 4.1) H_2 $v = 1 \rightarrow 0$ $S(1)$ surface brightness along the Galactic plane has a roughly constant value of $\sim 3 \times 10^{-5}$ ergs s^{-1} cm^{-2} sr^{-1}. Any excitation mechanism for the H_2 must be able to explain both the absolute intensity and the uniformity and extent of the emission. The excitation of the H_2 $v = 1$, $J = 3$ state can result either from radiative decay from UV-excited electronic states or from energetic collisions. H_2 can absorb 91–123 nm photons in the $B\ ^1\Sigma_u^+$–$X\ ^1\Sigma_g^+$ Lyman and $C\ ^1\Pi_u$–$X\ ^1\Sigma_g^+$ Werner bands. About 90% of the time, the excited H_2 decays to some ro-vibrational level of the ground electronic state. The relative line intensities that arise in UV-excited H_2 are insensitive to density or to UV field strength if $n_{H_2} < 10^4$ cm^{-3} (Black & van Dishoeck 1987). At densities $\geq 10^5$ cm^{-3}, UV-excited gas can become hot enough that collisions populate states with $v = 1$ (Sternberg & Dalgarno 1989). Collisional excitation can also result from shocks that abruptly heat the gas to greater than 10^3 K (see, e.g., Hollenbach, Chernoff, & McKee 1989). Several observational results lead us to believe that UV excitation can explain the $v = 1 \rightarrow 0$ $S(1)$ emission in the Galactic center.

The denser parts of clouds like Orion and NGC 2024 produce H_2 emission with an intensity close to that observed in the Galactic center. In Orion and NGC 2024, the degree-scale H_2 emission has a typical surface brightness of $\sim 6 \times 10^{-6}$ ergs s^{-1} cm^{-2} sr^{-1} (Luhman et al. 1994). Along the molecular ridges in these clouds, the H_2 surface brightness is 3–5 times higher. Observations of H_2 transitions arising from higher lying states indicates that, in these sources, the $v = 1 \rightarrow 0$ $S(1)$ emission is a result of UV fluorescence.

If large-scale H_2 emission arises in the surface layers of the clouds where UV photons can excite the molecules, the dust, which absorbs the bulk of the incident flux, ought to radiate in the far-IR continuum as well. Luhman & Jaffe (1996) have compared the H_2 $v = 1 \rightarrow 0$ $S(1)$ observations of clouds in the Galactic disk with *IRAS* far-IR continuum results and derived a relation between the H_2 $v = 1 \rightarrow 0$ $S(1)$ line and far-IR continuum intensities. We can use this relationship and the measured far-IR intensities in the Galactic center to see if UV excitation is plausible for our observed $v = 1 \rightarrow 0$ $S(1)$ emission. In most of the region along our Galactic center H_2 cut, the *IRAS* 100 μm–band detectors were saturated. In order to compare the Galactic center H_2 data to far-IR continuum measurements with comparable angular resolution, we have combined the unsaturated *IRAS* measurements from the outer ends of our H_2 strip with the 40–250 μm continuum measurements of Odenwald & Fazio (1984). To make the two data sets comparable, we first converted the *IRAS* 60 μm and 100 μm fluxes into a total far-IR flux (the FIR parameter of Fullmer & Lonsdale 1989). The *IRAS* total far-IR flux agrees well with the far-IR flux derived by Odenwald & Fazio in the regions where their data and the unsaturated *IRAS* data overlap. We then converted the combined data sets into integrated far-IR intensity for comparison with our H_2 strip. We used the Luhman & Jaffe Galactic disk H_2 data set to rederive their H_2/far-IR relation in intensity units. We obtain

$$\log I_{H_2\ v=1-0\ S(1)} = -4.65 + 0.39 \log I_{\rm FIR},$$

where both intensities are in ergs s^{-1} cm^{-2} sr^{-1}. The dispersion of the Galactic disk cloud H_2 intensities about this relation is $\log \sigma = 0.23$. If we deredden the Galactic center H_2 observations by $A_K = 2.5$ mag (*but otherwise do nothing to fit the data to the Galactic disk relation*), the Galactic center H_2 intensities have a dispersion $\log \sigma = 0.26$ about this relation. The Galactic center results are therefore completely consistent with the empirical far-IR versus H_2 relationship derived for the UV-excited surfaces of clouds in the Galactic disk.

We can also compare the H_2 line intensities predicted by models of PDRs to the observed intensities. The models use indirect observations of the far-UV field in the Galactic center (radio and far-IR continuum fluxes) as inputs. For the radio, we predict the far-UV field using emission from ELD H II regions because the molecular cloud column densities, and therefore the extinction at the wavelength of H_2, tend to be high (and uncertain) toward the discrete H II regions. Away from discrete H II regions, the typical 10.5 GHz flux density is 2.2 Jy in a 3'.3 beam (Sofue 1985). Assuming $T_e = 10^4$ K, this flux density corresponds to 2.3×10^{49} Lyman continuum photons per second (Mezger, Smith, & Churchwell 1974) in the corresponding region (8.2 pc). For an ionizing source with an effective stellar temperature $T_{\rm eff} = 3.5 \times 10^4$ K as the UV source, the 2.3×10^{49} Lyman continuum photons imply $\sim 2.3 \times 10^{49}$ photons in the range that can excite the H_2 (91–123 nm), or a luminosity of 1.2×10^5 $L_\odot$ (Black & van Dishoeck 1987). From our observations, the average H_2 flux in a 3'.3 beam is 2.4×10^{-12} ergs s^{-1} cm^{-2}. The corresponding total H_2 luminosity in the 8.2 pc (3'.3) region is 3.3×10^3 $L_\odot$, if we correct for an extinction of $A_K = 2.5$ mag and use the PDR model of Black & van Dishoeck (1987) to extrapolate to the H_2 cooling in all lines [$I_{H_2\ v=1-0\ S(1)}/I_{H_2} = 0.016$]. The ratio of the near-IR H_2 luminosity to the luminosity in the far-UV band that is effective in exciting H_2 is 0.028, which is close to the value of 0.034 from an appropriate PDR model for the Galactic center (model 19 in Black & van Dishoeck 1987, which has $n_H = 10^4$ and a UV field $I_{UV} = 10^3$).

The far-IR continuum intensities along our Galactic center strip are typically 0.8 ergs s^{-1} cm^{-2} sr^{-1} (Odenwald & Fazio 1984). If all of this emission arises from a single molecular cloud surface filling the beam, it corresponds to a far-UV flux of $\sim 2 \times 10^3$ times the mean interstellar radiation field in the solar neighborhood (Draine 1978). Given the likely number of clouds along each line of sight and various geometric effects, the likely far-UV field is 500–1000 times the solar neighborhood value. For this range of UV field strengths and densities between 3×10^3 and 3×10^4 cm^{-3}, Black & van Dishoeck (1987) predict H_2 $v = 1 \rightarrow 0$ $S(1)$ line intensities in the range $(1.2–4.2) \times 10^{-5}$ ergs s^{-1} cm^{-2} sr^{-1}, bracketing our typical observed, dereddened value.

The H_2 emission from the circumnuclear disk appears to be collisionally excited [$I_{v=2-1\ S(1)}/I_{v=1-0\ S(1)} \simeq 0.1$; Gatley et al. 1984]. Gatley et al. suggested that shocks created by mass outflow from the Galactic nucleus might excite the H_2. Such thermal line ratios can also occur, however, in UV-excited gas if the UV fields and densities are sufficiently high (Sternberg & Dalgarno 1989; Luhman et al. 1996). Since the typical hydrogen density in the circumnuclear disk is large, i.e., $n_H \simeq 10^5$ cm^{-3}, and the UV field is intense in the central 3 pc (the number of total Lyman continuum photons absorbed by the gas is $\sim 2 \times 10^{50}$ $L_\odot$; Lacy et al. 1980), the strength and character of the H_2 emission from the circumnuclear disk are also consistent with UV excitation.

4.3. *Shock-Excitation*

Shock-excitation of the H_2 $v = 1 \rightarrow 0$ $S(1)$ transition must take place, at some level, in the inner 400 pc of the Galaxy. A large variety of dynamical activity may give rise to shocks with appropriate characteristics. Outflows around newly formed stars and shocks caused by supernova remnants' impinging on molecular clouds in the Galactic disk both produce H_2 emission and should be observable in the Galactic center. Bally et al. (1987, 1988) surveyed the Galactic center region in the ^{12}CO and ^{13}CO $J = 1 \rightarrow 0$ and CS $J = 2 \rightarrow 1$ lines. The gas distribution is highly asymmetric about the center, and some negative-velocity gas is seen at positive longitudes, which is "forbidden" to gas in circular orbits. This gas and other clouds with eccentric orbits may collide with material in more circular orbits. For example, Hasegawa et al. (1994) suggested that in the Sgr B_2 complex a dense ($n_{H_2} \simeq 1.4 \times 10^4$ cm^{-3}), 10^6 $M_\odot$ "clump" has collided with the extended, less dense "shell" of the cloud complex, producing a ~30 km s^{-1} shock. Finally, the internal velocity dispersion of the molecular clouds is in the range $\Delta V = 20$–50 km s^{-1} (Bally et al. 1988). If the internal collisions efficiently dissipate the relative kinetic energy by radiative cooling following shocks, there should be H_2 emission throughout the molecular clouds, much of it, however, heavily extincted.

Depending on the context, shock-excited H_2 emission could result either from dissociative J-shocks (colliding clouds, supernova remnants) or from C-shocks (outflows, dissipation of turbulence). The J-shocks give rise to H_2 $v = 1 \rightarrow 0$ $S(1)$ intensities in the range 3×10^{-5} to 10^{-4} ergs s^{-1} cm^{-2} sr^{-1}, with the intensity's being fairly insensitive to density and shock velocity over the range 10^4 cm^{-3} $\leq n \leq 10^5$ cm^{-3} and 30 km s^{-1} $\leq V_{\rm shock} \leq 150$ km s^{-1} (Hollenbach & McKee 1989). For $A_K = 2.5$ mag, the predicted intensity matches what we observe in the Galactic center fairly well. In order to explain the distribution of observed H_2 emission, however, the number of shock fronts times the area covered per beam must roughly equal the beam area along virtually every line of sight through the inner 400 pc of the Galaxy, an unlikely picture at best.

C-shocks can produce H_2 $v = 1 \rightarrow 0$ $S(1)$ intensities in the range of those observed in the Galactic center. A single C-shock with $n = 10^4$ cm^{-3} and $V = 20$ km s^{-1} gives $I_{S(1)} \simeq 3 \times 10^{-5}$ ergs s^{-1} cm^{-2} sr^{-1} (Draine, Roberge, & Dalgarno 1983). The emergent intensity, however, is extremely sensitive to the shock's velocity, varying (at $n_{\rm H} = 10^4$ cm^{-3}) by 3 orders of magnitude from $V_{\rm shock} = 18$ to $V_{\rm shock} = 40$ km s^{-1}. A model that makes use of C-shocks to produce the observed uniform H_2 $v = 1 \rightarrow 0$ $S(1)$ distribution would have to be somewhat contrived. While there may be some shock-excited H_2 emission from the Galactic center, it is difficult to argue away the expected PDR emission and then construct a reasonably simple shock model capable of explaining the observations. A reliable test of the excitation mechanism would be to observe H_2 transitions arising higher above ground than the $v = 1 \rightarrow 0$ $S(1)$ line.

4.4. *Total* H_2 *Luminosity*

To estimate the total H_2 luminosity of the Galactic center, we extrapolate from our 400 pc–long strip by assuming that the scale height of the H_2 emission equals that of the far-IR radiation ($h \simeq 0.^\circ 2$; Odenwald & Fazio 1984). For $A_K = 2.5$ mag and $f \leq 1$ (see § 4.1), the dereddened H_2 $v = 1 \rightarrow 0$ $S(1)$ luminosity in the inner 400 pc diameter of the Galaxy is 8.0×10^3 $L_\odot$. Joseph (1989) gives ranges of H_2 $v = 1 \rightarrow 0$ $S(1)$ luminosity in greater than 1 kpc regions for various classes of galaxies: (1) merging galaxies: 3×10^6–3×10^8 $L_\odot$; (2) interacting galaxies: 10^5–10^7 $L_\odot$; (3) barred spirals: 10^4–10^6 $L_\odot$. Over its inner ~1 kpc, our Galaxy most likely falls within the range for barred spirals.

In ultraluminous IR-bright galaxies ($L_{\rm IR} \gtrsim 10^{12}$ $L_\odot$), Goldader et al. (1995) show that log $[L_{S(1)}/L_{\rm FIR}] = -4.95 \pm 0.22$. For the nearby starburst M82, we can use H_2 $v = 1 \rightarrow 0$ $S(1)$ measurements of the inner 60″ (S. Pak & D. T. Jaffe, unpublished) together with far-IR continuum observations (D. A. Harper, as quoted in Lugten et al. 1986) to derive log $[L_{S(1)}/L_{\rm FIR}] = -5.2$ for the inner 1 kpc. For the inner 400 pc of the Milky Way, the data presented here yield log $[L_{S(1)}/L_{\rm FIR}] = -4.8$.

There is evidence in some high-luminosity galaxies that the H_2 emission results from UV excitation. In NGC 3256, a merging galaxy, the H_2 $v = 2 \rightarrow 1$ $S(1)$/$v = 1 \rightarrow 0$ $S(1)$ line ratio in the 600 pc region (3″.5 × 3″.5) is 0.39 ± 0.06, which suggests that UV fluorescence is responsible for at least 60% of the H_2 $v = 1 \rightarrow 0$ $S(1)$ emission (Doyon, Wright, & Joseph 1994). If H_2 in the Galactic center is UV-excited, as we suggest here, this mechanism could be shared by H_2 emission from galaxies with an enormous range of nuclear conditions.

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