NEAR-IR H$_2$ EMISSION OF PROTOSTARS: PROBING CIRCUMSTELLAR ENVIRONMENTS

THOMAS P. GREENE$^1$, MARY BARSONY$^{2,3}$, AND DAVID A. WEINTRAUB$^4$

$^1$ NASA Ames Research Center, M.S. 245-6, Moffett Field, CA 94035, USA; tom.greene@nasa.gov
$^2$ Department of Physics and Astronomy, San Francisco State University, 1600 Holloway Drive, San Francisco, CA 94132, USA; mbarsony@SpaceScience.org
$^3$ Space Science Institute, 4750 Walnut Street, Suite 205, Boulder, CO 80301, USA
$^4$ Department of Physics and Astronomy, Vanderbilt University, Nashville, TN 37235, USA; david.a.weintraub@vanderbilt.edu

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ABSTRACT

We present new observations of near-infrared molecular hydrogen (H$_2$) line emission in a sample of 18 Class I and flat-spectrum low-mass protostars, primarily in the Tau-Aur and ρ Oph dark clouds. The line emission is extended by up to several arcseconds (several hundred AU) for most objects, and there is little night-to-night variation in line strength coincident with the continuum point source. Flux ratios of H$_2$ $v = 2–1$ $S(1)$ and $v = 1–0$ $S(1)$ lines are consistent with this emission arising in jets or winds in many objects. However, most objects have only small offsets (under 10 km s$^{-1}$) between their H$_2$ and photospheric radial velocities. No objects have line ratios which are clearly caused solely by UV excitation, but the H$_2$ emission of several objects may be caused by UV or X-ray excitation in the presence of circumstellar dust. There are several objects in the sample whose observed velocities and line fluxes suggest quiescent, non-mechanical origins for their molecular hydrogen emissions. Overall, we find the H$_2$ emission properties of these protostars to be similar to the T Tauri stars studied in previous surveys.

Key words: infrared: stars – ISM: jets and outflows – stars: formation – stars: pre-main sequence – techniques: spectroscopic

1. INTRODUCTION

Embedded low-mass protostars have been identified from their infrared (IR) energy distributions for over two decades, but their high extinctions and relatively small sizes make it very difficult to observe how radiation from the central protostars interacts with their inner, pre-planetary circumstellar disks. Recent high-sensitivity, high-resolution spectroscopic surveys have revealed the detailed stellar properties of significant numbers of these objects (Doppmann et al. 2005; White & Hillenbrand 2004; Greene & Lada 2002), but less is known about the physical conditions in their disks, especially of the gaseous component, or about their inner disks where planets might form and migrate. Here, we explore the gaseous component of the innermost regions of self-embedded (Class I and flat-spectrum; hereafter FS) protostars via high-resolution near-infrared (NIR) spectroscopy of the most abundant molecule in proto-planetary disks, molecular hydrogen (H$_2$). Near-infrared H$_2$ transitions are used, since the high extinctions to these sources preclude UV spectroscopy.

The NIR ro-vibrational lines of H$_2$ are good tracers of physical conditions in inner circumstellar disks and winds close to protostars. There are several different mechanisms that might be responsible for the production of NIR H$_2$ emission lines in late-stage protostars. These include (1) shock heating of the ambient medium by winds or jets, (2) X-ray heating, or (3) UV-heating, level pumping, and fluorescence.

Protostars must accrete mass at mean rates of $\sim 10^{-6}$–$10^{-5} M_\odot$ yr$^{-1}$ to assemble themselves on timescales of several 10$^3$ yr, and these high rates produce significant UV flux when the accreting matter impacts the stellar surface (e.g., Gullbring et al. 2000). Protostars and T Tauri stars are also known to be strong and variable sources of X-ray emission (e.g., Imanishi et al. 2001, 2003; G"udel et al. 2007; Flaccomio et al. 2009). Both UV and X-rays can excite vibrational states of H$_2$, producing NIR line emission (e.g., Gredel & Dalgarno 1995; Nomura et al. 2007). Many protostars and T Tauri stars also shed mass in jets that drive molecular outflows, and these jets also frequently excite NIR vibrational H$_2$ line emission (Zinnecker et al. 1998).

The most commonly encountered excitation mechanism for NIR H$_2$ emission associated with protostars to date has been shock excitation$^5$ (e.g., Davis et al. 2010), consistent with many self-embedded protostars being associated with large-scale molecular outflows (e.g., Moriarty-Schieven et al. 1992). These outflows are understood to be driven by powerful stellar winds (Masson & Chernin 1993). Such winds are often detected as blueshifted absorption components in forbidden emission lines or in the He$_\text{i}$ 1.0830 $\mu$m line associated with protostars and young T Tauri stars (e.g., Edwards et al. 1993; Kwan et al. 2007). Winds are also believed to cause the shocked IR H$_2$ emission seen in jets from heavily extinguished young stellar objects (YSOs). Such stellar winds are inferred to be driven by mass accretion onto young stars. Jets detected in NIR H$_2$ lines frequently are displaced in space and in radial velocity from photospheric absorption features and usually have relatively large linewidths of a couple dozen km s$^{-1}$ or more. For example, in a recent VLT/ISAAC pilot study of the H$_2$ 1–0 $S(1)$ emission from embedded Class I sources, mean intensity-weighted velocities were blueshifted by $\sim 90$ to $\sim 10$ km s$^{-1}$ and velocity widths of the lines varied from $\sim 45$ km s$^{-1}$ to $\sim 80$ km s$^{-1}$ (Chrysostomou et al. 2008).

X-rays and UV may also excite molecular hydrogen emission in the inner circumstellar environments of protostars. Both of these processes offer a radiative alternative to the mechanical excitation excitation of the NIR H$_2$ emission. If dominant, these excitation mechanisms may produce emission lines with lower...
velocity widths or offsets than if the H$_2$ were mechanically excited in shocks or jets. We now consider the mechanisms, observational evidence, and implications for these processes in protostellar environments.

It is now well established that Class I/FS protostars are copious X-ray emitters ($10^{29} \leq L_x \leq 10^{31}$ erg s$^{-1}$, $\sim$100–1000 times more X-ray luminous than main-sequence stars) and emit higher energy X-rays (4–6 keV versus 1–2 keV) than their older, T Tauri cousins (e.g., Casanova et al. 1995; Grosso et al. 1997; Imanishi et al. 2001; Feigelson et al. 2007). One would, therefore, expect significant X-ray heating of the disk/inner envelope material surrounding these central objects (e.g., Meijerink et al. 2009, 2007). X-rays from YSOs can penetrate disk atmospheres to fairly large surface densities and can ionize circumstellar gas at a level greater than Galactic cosmic rays out to large distances ($\sim$10$^4$ AU; Glassgold et al. 2005).

The mechanism of H$_2$ excitation by X-rays requires impacts from energetic electrons. X-rays impact hydrogen molecules, ejecting electrons. These high-energy electrons subsequently collide with and ionize or dissociate ambient gas, losing kinetic energy in the process. Some of the electrons will eventually have energies appropriate to excite ambient H$_2$ molecules into excited states instead of dissociating them completely (e.g., Gredel & Dalgarno 1995; Tine et al. 1997; Maloney et al. 1996). Direct evidence for X-ray heating of gas other than H$_2$ in disks has been found for several Class I sources in which the 6.4 keV line from neutral iron has been detected (Giardino et al. 2007, and references therein).

Glassgold and co-workers in particular have emphasized the importance of X-ray heating of disk atmospheres out to relatively large distances from the central source (Glassgold et al. 2004, 2007). Such heating can extend to large distances because of disk flaring, first proposed to account for the spectral energy distributions produced by dust (Kenyon & Hartmann 1987; Chiang & Goldreich 1997). More recent disk modeling, especially studies involving disk chemistry, routinely uses vertically stratified models, with different gas and dust scale heights (d’Alessio et al. 1999; Aikawa et al. 2002; Gorti & Hollenbach 2008; Lacy et al. 2010). In X-ray heated disk models, there is a low column density ($N_H \sim 10^{20}$ cm$^{-2}$) surface layer of hot ($T \sim 4000$ K) gas that extends to $\gtrsim 10$ AU radius (Najita et al. 2009).

In the context of disk heating by X-rays, it must be noted that current disk models assume irradiation by a central source with X-ray spectra typical of T Tauri stars: with plasma having $kT_X = 1$ keV and a low-energy cut-off of 100 eV (e.g., Glassgold et al. 2007). However, Class I and FS sources are known to have higher X-ray spectra, with 4 keV $\lesssim kT_x \lesssim 6$ keV being typical (e.g., Imanishi et al. 2001). Unsurprisingly, the column densities of hydrogen gas inferred toward Class I/FS sources from X-ray observations are $\sim N_H = 1$–5 $\times 10^{22}$ cm$^{-2}$, 1–2 orders of magnitude greater than inferred for T Tauri stars. Finally, the quantity $L_x/L_{bol}$ is systematically smaller for Class I/FS objects relative to T Tauri stars, consistent with the interpretation of higher accretion rates in these systems. The higher accretion rates create higher optical depths in the X-ray absorbing gas, obscuring the lower energy X-rays and producing relatively lower $L_x/L_{bol}$ ratios. Higher accretion rates would also lead to higher heating rates of the disk gas in self-embedded protostars than in classical T Tauri star (CTTS) disks (e.g., d’Alessio et al. 2004).

The possibility of UV excitation of the NIRT H$_2$ lines also exists for Class I/FS protostars, given their consistently higher accretion rates relative to T Tauri stars. The excess UV continuum emission observed in CTTSs has been modeled as being produced by the impact of accretion columns onto the pre-main-sequence stellar surface (e.g., Gullbring et al. 2000). This UV continuum excess could potentially excite molecular hydrogen, producing emission lines in the near-infrared. Strong Ly$\alpha$ emission from the central object can irradiate the disk’s surface and, if H$_2$ is present at $\sim$2000 K, can excite the H$_2$ into electronic states which produce a rich UV emission-line spectrum as observed in some T Tauri stars (Herczeg et al. 2006). Finally, if the stellar EUV flux is sufficiently strong, it can ionize hydrogen, which produces high temperatures ($T \approx 10^4$ K) and small mean molecular weights at the disk surface. Outside some critical radius, the gas becomes unbound and a slow, $v \approx 10$ km s$^{-1}$, photoevaporative wind forms (Alexander et al. 2006a, 2006b; Gorti et al. 2009; Woitke et al. 2009).

Like molecular hydrogen, [Ne II] emission can also arise from high-energy photons in dense circumstellar disks or outflows. [Ne II] line emission at 12.81 $\mu$m and [Ne II] emission at 15.5 $\mu$m were predicted to be detectable in the case of X-ray heated disk gas. The 12.81 $\mu$m [Ne II] line has subsequently been detected in a number of young stars with the Spitzer Space Telescope (Glassgold et al. 2007; Pascucci et al. 2007; Lahuis et al. 2007; Flaccomio et al. 2009; Najita et al. 2010) and has been studied at high spectral resolution from the ground in three objects (Herczeg et al. 2007; Najita et al. 2009). Although a disk origin has been postulated or confirmed for the [Ne II] emission observed in the objects studied at high spectral resolution, there are also sources in which [Ne II] is detected in outflows close to the sources (e.g., Neufeld et al. 2006; van Boekel et al. 2009).

In general, gas motions in the inner circumstellar environments (within $\sim$100 AU) of protostars have not been studied well except for a very few cases of velocity resolved NIR CO observations, and this has limited our understanding of how they accrete matter, form winds, shed angular momentum, and disperse their natal circumstellar envelopes. We seek to understand these processes as well as the UV and X-ray radiation environments of their circumstellar disks by embarking on a new study of protostars’ H$_2$ line strengths, morphologies, and velocities. H$_2$ NIR ro-vibrational line ratios yield excitation temperatures and also provide clues to excitation mechanisms. The intensity ratio of $S(1)$ lines in the $v = 2 \rightarrow 1$ and $v = 1 \rightarrow 0$ transitions is often used as a diagnostic. This ratio has a value of 0.13 in shocked gas at 2000 K and a value of 0.54 for UV pumping. For X-ray excitation, this ratio is predicted to be 0.06 in gas of low fractional ionization ($10^{-4}$) and 0.54 in gas of high fractional ionization ($10^{-2}$; Gredel & Dalgarno 1995). Any observed variability in these emission lines can also provide clues to the nature of their excitation and the location of the excited and emitting gas.

Several recent studies have made good progress in diagnosing the nature of H$_2$ excitation in the inner circumstellar disks of CTTSs using observations of their NIR ro-vibrational emission lines. A growing body of work shows that the NIR H$_2$ line radial velocities and linewidths of many CTTS and Herbig AeBe stars are consistent with UV or X-ray excitation in a circumstellar disk (Weintraub et al. 2000; Bary et al. 2002, 2003; Carmona et al. 2007; Bary et al. 2008). By contrast, in a recently completed NIR adaptive optics (AO) integral field spectroscopic study of several CTTS, the H$_2$ emissions were most consistent with shocks arising in winds (Beck et al. 2008).

Despite this progress in understanding H$_2$ emission in CTTSs, little has been done to date to probe the nature of such emission
in more embedded Class I and FS protostars, Greene & Lada (1996) reported that these protostars were significantly more likely to have NIR H₂ emission than CTTSs, and Doppmann et al. (2005) found that 23 of 52 observed protostars showed NIR H₂ emission. The most embedded protostars also have significant envelopes that may have enough column density to generate observable H₂ emission if the hydrogen molecules there receive sufficient radiative or mechanical energy. If this envelope source existed, it would be a new source of emission not present in CTTSs. Unfortunately, earlier studies did not have adequate spectral resolution or spectral range to observe multiple NIR ro-vibrational lines simultaneously with high spectral resolution and good signal-to-noise—all necessary ingredients for measuring line velocities and line ratios in order to diagnose excitation.

An early motivation for a new observational study was the identification of outflow drivers amongst late-stage protostars via detection of NIR H₂ emission at high spectral resolution observed directly toward the putative powering source (Barsony 2005). However, careful examination of the H₂ v = 1–0 S(0) line profiles (at 2.2235 μm) observed at R ~ 17,000 in the work of Doppmann et al. (2005) showed that a substantial number of sources exhibited relatively narrow linewidths (Δλ ~ 15 km s⁻¹). Furthermore, in many cases, the H₂ emission line centers were not significantly displaced from the central object’s radial velocity. Taken together, these two observations call into question an outflow origin for the observed NIR H₂ emission in some sources.

We have conducted a new study of Class I and FS protostars with data sufficient to diagnose the nature of their H₂ emission in their inner circumstellar disks and envelopes. We report on the sample and observations in Section 2, and present our analysis of these data in Section 3. We serve as radial velocity references.

2. OBSERVATIONS AND DATA REDUCTION

High-resolution NIR spectra of 18 Class I and FS protostars previously searched for H₂ v = 1–0 S(0) emission by Doppmann et al. (2005) were re-observed with the Keck II telescope on Mauna Kea, Hawaii, using its NIRSPEC multi-order cryogenic echelle facility spectrograph (McLean et al. 1998). This included 17 objects found to exhibit H₂ v = 1–0 S(0) emission in this previous study, and 1 (03260+311A) without. All new spectra were acquired on 2007 June 24 and 25 UT (ρ Oph and Ser objects) and 2008 January 24 and 25 (Tau-Aur and Per objects). The late-type (K1–M2.5) dwarfs HD 28354, HR 6070, HR 5993, and HD 168966 were observed for telluric correction of the target spectra. The telescope was automatically guided with frequent images from the NIRSPEC internal “SCAM” IR camera during all exposures of more than several seconds’ duration. Spectra of the internal NIRSPEC continuum lamp were taken for flat fields, and exposures of the Ar, Ne, Kr, and Xe lamps were used for wavelength calibrations.

All data were reduced with IRAF. First, object and sky frames were differenced and then divided by normalized flat fields. Next, bad pixels were fixed via interpolation, and spectra were extracted with the APALL task. Spectra were wavelength calibrated using low-order fits to lines in the arc lamp exposures, and spectra at each slit position of each object were co-added. Instrumental and atmospheric features were removed by dividing wavelength-calibrated object spectra by spectra of early-type stars observed at similar air mass at each slit position. Final spectra were produced for each night by combining the spectra of both slit positions for each object and then multiplying them by spectra of 10,000 K blackbodies to rectify the spectral shapes induced when dividing by the telluric stars with that effective temperature. Spectra acquired on different nights were not combined in any way.

3. ANALYSIS AND RESULTS

The spectra of all objects in Table 1 were analyzed by measuring their H₂ v = 1–0 S(1), v = 2–1 S(1), and v = 1–0S(0) line fluxes, H₂ line radial velocities, and the radial velocities of photospheric absorption lines. The 2.386 μm H₂ v = 3–2 S(1) line is in a region of poor atmospheric transmission and was not significantly detected in any object. The values of the H₂ line properties and their night-to-night variations were analyzed for physical insights into their excitation as described in this section.

Spectra of the H₂ v = 1–0 S(1) region are shown for all objects in Figure 1; the first epoch (2007 June 24 and 2008 January 24) is shown in the left panel and the second (2007 June 25 and 2008 January 25) in the right. Of the 18 objects, 14 were observed in both epochs. When present, the v = 1–0 S(1) line was the strongest H₂ feature observed in all objects. All emission spectra shown in the figures and all derived strength and velocity values presented in Table 2 are for the H₂ emission that was spatially coincident with each object’s continuum source, typically limited by the 0.6″ seeing, corresponding to a spatial extent of ~100 AU for most sources.

3.1. H₂ Emission Morphologies

The spatial extent of the H₂ emission along the spectrograph slit was measured for each object by examining the differenced and flat-fielded spectral images that were created prior to...
The angular extent of the H$_2$ emission along the length of the slit is reported in Table 2 for each observation. Ten of the 18 protostars showed H$_2$ emission that was over 1″ in spatial extent in at least one observation (at least one position angle). Of the 14 objects observed in two epochs, 6 had H$_2$$ _1$$ ^{-1}$$ _0$ S(1) emission extended by ~1″ or less on both nights. Therefore the molecular hydrogen emission of these six objects is contained within about 70 AU (~0.5) of their central stars. The highest H$_2$ surface brightness was generally found to be coincident with each object’s unresolved point source, but in some cases the extended emission may have more integrated flux and luminosity than the point source component. Beck et al. (2008) found this to be true in their AO integral field study of several CTTSs that sampled their immediate circumstellar environments completely instead of evaluating just two slit position angles as done in this study.

Objects with significantly different spatial extents between epochs (position angles) may have their H$_2$ emission confined to asymmetrical structures like jets. 03260+3111B, 04158+2805, and 04264+2433 are examples of objects with these potentially jet-like morphologies. 03260+3111A shows significantly extended emission, but this is spatially displaced from the stellar continuum which has no coincident H$_2$ emission.

Table 1: Journal of Observations

| Object     | Region | α(2000) (hh mm ss.s) | δ(2000) (° ′ ″) | UT Date   | Int. Time (minutes) | Slit P.A. (°E of N) |
|------------|--------|-----------------------|-----------------|-----------|---------------------|-------------------|
| 03260+3111B | Per    | 03 29 07.7           | 31 21 58        | 2008 Jan 24 | 20.0                | 103               |
| 03260+3111A | Per    | 03 29 10.7           | 31 21 59        | 2008 Jan 24 | 20.0                | 118               |
| 04108+2803B | Tau-Aur | 04 13 54.9           | 28 11 31        | 2008 Jan 24 | 20.0                | -123              |
| 04158+2805  | Tau-Aur | 04 18 58.2           | 28 12 24        | 2008 Jan 24 | 20.0                | 73                |
| 04181+2654AB| Tau-Aur | 04 21 11.5           | 27 01 09        | 2008 Jan 24 | 10.0                | 48                |
| DG Tau     | Tau-Aur | 04 27 04.8           | 26 06 17        | 2008 Jan 25 | 10.0                | 57                |
| 04264+2433 | Tau-Aur | 04 29 30.0           | 24 39 56        | 2009 Jan 24 | 12.0                | 57                |
| 04295+2251 | Tau-Aur | 04 32 32.1           | 22 57 27        | 2009 Jan 24 | 40.0                | -106              |
| 04361+2547 | Tau-Aur | 04 39 13.5           | 25 53 20        | 2008 Jan 24 | 12.0                | 68                |
| 04365+2535 | Tau-Aur | 04 39 35.2           | 25 41 45        | 2008 Jan 24 | 12.0                | -110              |
| GSS 30     | Oph    | 16 26 21.4           | -24 23 06       | 2007 Jun 25 | 14.0                | -124              |
| GY 21      | Oph    | 16 26 23.6           | -24 24 38       | 2007 Jun 25 | 20.0                | -56               |
| WL 12      | Oph    | 16 26 44.1           | -24 34 48       | 2007 Jun 25 | 8.0                 | -47               |
| WL 6       | Oph    | 16 27 21.6           | -24 29 51       | 2007 Jun 24 | 20.0                | -72               |
| IRS 43     | Oph    | 16 27 27.0           | -24 40 50       | 2007 Jun 24 | 45.0                | -78               |
| YLW 16A    | Oph    | 16 27 27.8           | -24 39 32       | 2007 Jun 25 | 12.0                | -85               |
| IRS 67     | Oph    | 16 32 01.1           | -24 56 45       | 2007 Jun 24 | 60.0                | -59               |
| SVS 2      | Ser    | 18 29 56.8           | 01 14 46        | 2007 Jun 25 | 28.0                | -85               |

3.2. Variability

We found H$_2$ emission in all of the 17 objects also found to have H$_2$ emission at earlier epochs by Dopmann et al. (2005). The one source without emission (03260+3111A) in that earlier study also did not show H$_2$ emission in our new observations. This indicates that these protostars do not terminate or initiate their H$_2$ emissions on timescales as short as 5–10 years, suggesting that their H$_2$ lines are emitted over physically large regions or else are excited by processes with relatively stable fluxes.

Fourteen of the 18 objects were observed twice, with the two observations spaced approximately 24 hr apart. The position angles of both observations were sometimes similar (within ~10°), but often they varied by 60° or more (Table 1). Therefore the different slit position angles must be considered when comparing H$_2$ line fluxes measured on the different dates to determine whether any differences are due to true temporal variation or the rotation of different spatial features (i.e., jets) onto or off of the slit. However, the measured equivalent H$_2$ emission widths and line velocities were similar for both observations of each object (see Table 2), so there appears to be little temporal variation on ~1 day timescales for the emission that is spatially confined to be coincident with the protostar continuum source confined within the slit width.

3.3. Radial Velocities and Line Widths

Stellar photospheric radial velocities were computed from the continuum absorption lines of all observed objects. First, spectral extraction. The non-rotating spectrograph slit was projected onto the sky at different position angles each night, so the two observational epochs sample the spatial extent of any extended emission differently (see position angles in Table 1).

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Figure 1. H$_2$ $v = 1$–$0$ $S(1)$ line spectra. Spectra acquired on 2007 June 24 and 2008 January 24 (first epoch) appear in the left panel, and spectra acquired on 2007 June 25 and 2008 January 25 (second epoch) appear in the right panel. These spectra were extracted only in the region containing the mostly point source continuum emission; any extended H$_2$ emission is not included.

the object spectra were cross-correlated (using fxcor in IRAF) with spectra of the radial velocity standards, always HD 28343 (K7 V) and sometimes HD 20165 (K1 V) or HD 285968 (M2.5 V), using up to four spectral orders that contained photospheric lines but no emission lines. Heliocentric $V_{\text{LSR}}$ radial velocities were computed for each object by summing the radial velocity shift measured with the cross-correlations, the mean measured radial velocities of the three standards (Nidever et al. 2002), and the $V_{\text{LSR}}$ corrections for the objects and standards at their time of observation (from the IRAF rvcorrect task). The $V_{\text{LSR}}$ radial velocities computed in this way generally agreed well with those of the 10 objects also reported by Covey et al. (2006). We observed these 10 objects a total of 18 times, and we measured the offset from the Covey et al. (2006) velocities to be $2.2 \pm 3.5$ km s$^{-1}$. This offset is consistent with zero, and the standard deviation is not surprising given the 17 km s$^{-1}$ spectral resolution and the generally heavily veiled spectra.

Radial velocities of H$_2$ lines were computed by measuring the central wavelengths of Gaussian profiles fitted to the lines using the IRAF splot task and then converting these values to velocities. These observed radial velocities were converted to $V_{\text{LSR}}$ values by adding the $V_{\text{LSR}}$ correction offset computed for each object as described above. The velocities of the H$_2$ lines relative to photospheric lines of each object were computed by differencing these two $V_{\text{LSR}}$ radial velocities, and the results are shown in Table 2 and Figure 2. FWHM velocity widths of the $v = 1$–$0$ $S(1)$ lines were computed by subtracting the instrumental line width of 17 km s$^{-1}$ in quadrature from the FWHM values of the Gaussian fits. These resultant line widths are also reported in Table 2, and their histogram is shown in Figure 3. Objects observed twice on successive nights had similar radial and FWHM velocities (Table 2), so these values were averaged to reduce noise in Figures 2 and 3. The other H$_2$ lines generally had similar FWHM values, but the $v = 1$–$0$ $S(1)$ lines had the highest signal-to-noise, so only those values are presented. We estimate that all reported velocities have uncertainties of a few km s$^{-1}$.

3.4. H$_2$ Line Fluxes and Ratios

Line luminosities were estimated by scaling the relative fluxes measured in each H$_2$ line to the spatially coincident 2.2 μm
### Table 2

**Protostar H$_2$ Line Analysis**

| Source       | UT Date       | 1–0 S(0) EW (Å$^d$) | 1–0 S(1) EW (Å$^d$) | 2–1 S(1) EW (Å$^d$) | $A_v^a$ | 1–0 S(1) Log L(W) | 2–1/0–0 S(1) FWHM$^b$ (km s$^{-1}$) | V(H$_2$ - *$^c$) (km s$^{-1}$) | H$_2$ 1–0 S(1) extent ($^c$) |
|--------------|---------------|---------------------|---------------------|---------------------|--------|------------------|----------------------------------|---------------------------------|-------------------------------|
| 03260+3111B  | 2008 Jan 24$^e$ | 0.50                | 2.12                | 0.49                | 3.35   | 22.0             | 0.25                             | 43                              | $\geq10$                       |
|              | 2008 Jan 25   | 0.51                | 2.69                | 0.39                | 3.5    | 22.1             | 0.14                             | 44                              | $\leq1$                        |
| 03260+3111A$^d$ | 2008 Jan 24  | <0.1                | <0.1                | <0.1                | ...    | ...              | ...                              | ...                             | $\sim7$                        |
|              | 2008 Jan 25   | <0.1                | <0.1                | <0.1                | ...    | ...              | ...                              | ...                             | $\geq10$                       |
| 04108+2803B  | 2008 Jan 24   | 0.92                | 4.29                | 0.39                | 19     | 22.0             | 0.08                             | 18                              | $-1$                          |
|              | 2008 Jan 25   | 0.69                | 3.43                | 0.29                | 19     | 21.9             | 0.07                             | 18                              | $-1$                          |
| 04158+2805   | 2008 Jan 24   | 0.49                | 2.57                | 0.26                | 3.1    | 21.1             | 0.08                             | 20                              | $-4$                          |
|              | 2008 Jan 25   | 0.35                | 2.70                | 0.22                | 3.1    | 21.2             | 0.06                             | 20                              | $-4$                          |
| 04181+2654AB | 2008 Jan 24   | 0.23                | 1.46                | 0.04                | 23     | 22.0             | 0.00                             | 24                              | $-1$                          |
|              | 2008 Jan 25   | 0.39                | 1.37                | 0.00                | 23     | 21.9             | 0.00                             | 25                              | 8                             |
| DG Tau       | 2008 Jan 25   | 0.14                | 0.54                | 0.06                | 0      | 22.0             | 0.08                             | 14                              | $-9$                          |
| 04264+2433   | 2008 Jan 24   | 1.56                | 5.78                | 0.53                | 6.1    | 21.7             | 0.06                             | 10                              | $-2$                          |
|              | 2008 Jan 25   | 1.44                | 6.09                | 0.52                | 6.1    | 21.7             | 0.06                             | 13                              | $-4$                          |
| 04295+2251   | 2008 Jan 24   | 0.59                | 2.42                | 0.14                | 17     | 22.0             | 0.04                             | 16                              | $-2$                          |
|              | 2008 Jan 25   | 0.59                | 2.43                | 0.16                | 17     | 22.0             | 0.05                             | 16                              | $-2$                          |
| 04361+2547   | 2008 Jan 24   | 1.06                | 4.11                | 0.45                | 22     | 22.2             | 0.08                             | 14                              | $-3$                          |
|              | 2008 Jan 25   | 0.66                | 2.10                | 0.21                | 22     | 21.9             | 0.06                             | 13                              | $-3$                          |
| 04365+2535   | 2008 Jan 24   | 0.57                | 2.58                | 0.18                | 19     | 21.9             | 0.06                             | 19                              | $-3$                          |
|              | 2008 Jan 25   | 0.35                | 1.59                | 0.09                | 19     | 21.6             | 0.05                             | 16                              | $-3$                          |
| GSS 30       | 2007 Jun 25   | 0.53                | 2.35                | 0.20                | 20     | 22.6             | 0.07                             | 25                              | $-11$                         |
| GY 21$^f$    | 2007 Jun 24   | 0.37                | 1.80                | 0.20                | 16     | 21.8             | 0.07                             | 28                              | $-11$                         |
|              | 2007 Jun 25   | 0.52                | 2.21                | 0.20                | 16     | 21.9             | 0.07                             | 29                              | $<10$                         |
|              | 2008 Jan 25   | 1.43                | 12.4                | 0.79                | 18     | 22.1             | 0.06                             | 32                              | $-2$                          |
| WL 12        | 2007 Jun 25   | 2.06                | 11.0                | 0.73                | 18     | 22.1             | 0.06                             | 29                              | $-12$                         |
| WL 6         | 2007 Jun 24   | 0.06                | 0.34                | 0.06                | 37     | 21.6             | 0.15                             | 15                              | 0                             |
|              | 2007 Jun 25   | 0.09                | 0.37                | 0.03                | 37     | 21.6             | 0.16                             | 16                              | $-3$                          |
| IRS 43$^b$   | 2007 Jun 24   | 0.09                | 0.28                | 0.02                | 33     | 21.8             | 0.05                             | 9                               | 0                             |
|              | 2007 Jun 25   | 0.17                | 0.64                | 0.04                | 33     | 22.1             | 0.05                             | 22                              | $-4$                          |
| YLW 16A      | 2007 Jun 24   | 0.32                | 1.41                | 0.20                | 17     | 21.6             | 0.12                             | 25                              | 0                             |
|              | 2007 Jun 25   | 0.31                | 1.25                | 0.13                | 17     | 21.6             | 0.09                             | 28                              | $-4$                          |
| IRS 67       | 2007 Jun 24   | 0.13                | 0.37                | 0.03                | 22     | 21.1             | 0.07                             | 15                              | 0                             |
| SVS 2$^i$    | 2007 Jun 25   | 0.09                | 0.39                | 0.01                | 0      | 21.5             | 0.00                             | 13                              | 19                            |

**Notes.**

$^a$ $V$ magnitude extinction was computed using each object’s 2MASS $JHK$ colors, an extinction law, and estimated intrinsic CTTS locus colors as explained in the text in Section 3.4

$^b$ The mean FWHM velocity of the 1–0 S(1) H$_2$ line, where the intrinsic instrumental line width of 17 km s$^{-1}$ has been removed in quadrature.

$^c$ The radial velocity of the stellar photosphere subtracted from the mean radial velocity of the 1–0 S(0), 1–0 S(1), and 2–1 S(1) H$_2$ emission lines (uncertain lines not used). No data indicate that the star lacked either H$_2$ or photospheric lines.

$^d$ Positive equivalent widths indicate emission. Uncertainties are $\sim$0.02 Å for 2007 data and $\sim$0.05 Å for 2008 data.

$^e$ Spectrum displays $\Delta v = 2$–0 CO emission.

$^f$ The extended H$_2$ emission is spatially displaced from the star. No H$_2$ emission is coincident with the stellar continuum (as also observed by Dopmann et al. 2005).

$^g$ The H$_2$ emission slightly spatially displaced from the stellar continuum has velocity FWHM $\Delta v \sim 60$ km s$^{-1}$, about twice that of the H$_2$ emission spatially coincident with the stellar continuum.

$^h$ The H$_2$ line equivalent widths and luminosities are presented in Table 2, and a histogram of luminosities of the H$_2$ v = 1–0 S(1) line is shown in Figure 4. A histogram of H$_2$ 1–0/2–1 S(1) line ratios is presented in Figure 5. As done in previous figures, values derived from observations of objects acquired on successive nights are averaged in these figures as well. Note that the H$_2$ line ratio value plotted in Figure 5 is the inverse of the values presented in Table 2 (Column 8).
3.5. Correlations

We examined whether correlations exist between measured \( \text{H}_2 \) line properties and other protostellar activity indicators in an attempt to isolate the origins of the \( \text{H}_2 \) line emissions.

First we computed the correlations between the \( \text{H}_2 \) line properties measured in this new survey. The FWHM velocity widths and the \( 1-0/2-1 \) \( \text{S}(1) \) line ratios in Table 2 have a correlation coefficient of 0.61, which improves to 0.71 when both observations of a single object are averaged into single points. This value drops to only 0.17 (individual or mean values) if the observations of 03260+3111B are excluded; its high FWHM velocity and relatively high \( 1-0/2-1 \) \( \text{S}(1) \) line ratio drives this correlation. Thus the object sample as a whole
does not show a good correlation between its H2 FWHM velocities and 1–0/2–1 S(1) line ratios. We then examined correlations between H2 FWHM velocities and velocity offsets between H2 and photospheric lines. These values had correlation coefficients of −0.43 and −0.47 for individual and averaged values, respectively. The square of the correlation coefficient is below 0.25 in both cases, indicating that less than 25% of the variance of the two quantities is in common for this sample of protostars, a poor correlation.

Next we correlated the protostars’ H2 line properties with other physical characteristics measured in other studies. Twelve of the 18 objects have measured X-ray luminosities or upper limits (Güdel et al. 2007; Flaccomio et al. 2009), and the correlation coefficient between the logarithms of their H2 1–0 S(1) line luminosities and the logarithms of their X-ray luminosities is −0.20, suggesting a very weak or nonexistent inverse correlation between these properties. Finally, we reanalyzed the spectra of Doppmann et al. (2005) and used their equivalent width measurements of H2 1–0 S(0) and H1 Br γ emission lines to evaluate the correlation of these properties in that somewhat earlier epoch. We found that these values had a correlation coefficient of 0.20, indicating another poor correlation. In summary, we find little correlation among the NIR H2 line emission properties or between these properties and other young stellar activity indicators.

4. DISCUSSION

The different radiative and collisional excitation mechanisms of H2 are well matched to the radiative and mass flux processes in the environments of protostars and T Tauri stars. We now interpret the results of the preceding analysis in terms of several of these possible processes in order to constrain the H2 excitation mechanisms of the sample and to understand better the circumstellar environments of these protostars.

4.1. Emission Morphologies, Variability, and Velocities

In addition to their compact H2 line emissions, all but 4 of the 18 objects also showed $v = 1–0$ S(1) molecular hydrogen emission extended by $<1\prime$ or more along the slit (see Table 2), corresponding to 70 AU ($<0.5\prime$) or more projected radial distance. It is unlikely that UV radiation could travel that far from the central protostars without significant attenuation by gaseous and dusty envelopes, so it is likely that this extended emission is excited by either stellar winds or high-energy X-rays. The expected small size of the UV emission region on the protostellar photosphere also suggests that UV may not be a good candidate for exciting the observed steady and long-lived H2 line emissions. Two objects, GY 21 and IRS 43, have extended 1–0 S(1) emission with broad line widths, FWHM $\gtrsim 40$ km s$^{-1}$, about twice that of the compact emission spatially coincident with their stellar continua. The extended emissions of these two objects are good candidates for excitation in shocks caused by stellar winds.

The relatively stable values of the point source H2 emission over 1 day and several-year timescales (see Section 3.2 and Table 1) also provide clues to the nature of these emissions. Numerous Class I and FS protostars have been observed to undergo rapid (several hr) , large amplitude X-ray emission variations (e.g., Imanishi et al. 2001, 2003; Güdel et al. 2007; Flaccomio et al. 2009). This X-ray flaring of several protostars (e.g., IRS 43) has also been observed to appear or disappear in data taken $\sim$5–10 years apart. If these X-ray flares were exciting H2 close to the stars, then it is likely that we would see significant night-to-night or year-to-year variations in their point source near-IR line fluxes, but this is not seen in our data. The very stable observed molecular hydrogen emission is more consistent with mechanical (wind or jet) excitation as well as excitation by steady, non-flaring X-ray emission from the protostars.

The preceding analysis of the velocity widths and velocity shifts of the H2 line emission in Section 3.3 also provides clues to the nature of its excitation. Collisional excitations in jets or winds are likely to result in H2 emission line radial velocities displaced from photospheric absorption lines by over 10 km s$^{-1}$, exhibition of broad line wings, or large FWHM velocities of several 10 km s$^{-1}$ or more (Maloney et al. 1996; Montmerle et al. 2000; Nomura et al. 2007; Beck et al. 2008). Jets are also often significantly collimated and spatially extended, making them easy to identify in one- or two-dimensional spectral images (e.g., Schwartz & Greene 2003). The significant spatial extension of the H2 line emission of many objects is consistent with collisional excitation in winds or by jets. However, only 5 of 13 protostars show radial velocity offsets between their H2 lines and photospheric absorption lines with absolute value of greater than 4 km s$^{-1}$ (see Figure 2). This value is similar to the 3.5 km s$^{-1}$ uncertainty we measured for radial velocity standards (see Section 3.3), so we do not consider velocity offsets less than 4 km s$^{-1}$ to be significant. Only three protostars have velocity offsets of at least 10 km s$^{-1}$, significant at about the 3σ confidence level or greater. This evidence suggests that collisional excitation in jets is unlikely to be the molecular hydrogen excitation mechanism in most objects (except the three with significant velocity differences).

However, the on-source H2 $v = 1–0$ S(1) line FWHM line widths of all 17 protostars with this on-source feature are broader than 10 km s$^{-1}$ (see Figure 3). Six of the emitting objects (35%) exhibit FWHM greater that 20 km s$^{-1}$. All six of these objects also show spatially extended H2 emission many tens of AU from their central stars; this combination of factors makes them good candidates for collisional excitation in jets or winds. Seven of the emitting objects (41%) have FWHM line widths below 16 km s$^{-1}$. This is similar to the 9–14 km s$^{-1}$ line widths found by Bary et al. (2003) and Bary et al. (2008) for 8 of 10 T Tauri stars found to have H2 emission, which they interpreted as evidence for quiescent emission in circumstellar disks. We conclude that the molecular hydrogen emission line velocities and FWHM values of at least 3–6 of the 17 emitting objects are consistent with collisional excitation in jets, and at least 7 or 8 objects have H2 velocity parameters consistent with quiescent (non-collisional) excitation.

4.2. Emission Line Strengths and Ratios

NIR vibrational H2 line ratios are also sensitive to the gas excitation levels and excitation mechanisms. Greder & Dalgarno (1995) show that the ratios of the H2 $v = 1–0$ S(1) to $v = 2–1$ S(1) lines are relatively sensitive to excitation mechanisms. They compute the ratios of these two lines to be 1.9 for UV excitation, 7.7 for shocked gas at $T = 2000$ K, and 16.7 for X-ray excitation of low ionization H2. Black & van Dishoeck (1987) also found similar differences between UV and shock excitation of H2. However, there are limits to the usefulness of these ratios as diagnostics of excitation in circumstellar disks. In practice, it is difficult to distinguish between shocked and X-ray excited H2 emission from examining only a few NIR
lines. Collisions will thermalize the excitation levels of \( H_2 \) in a sufficiently dense gas, so \( v = 1 \rightarrow 0 \) \( S(1) \) to \( v = 2 \rightarrow 1 \) \( S(1) \) line ratios indicative of cold-to-warm gas in equilibrium are not always useful for distinguishing between excitation mechanisms (Gredel & Dalgarno 1995; Maloney et al. 1996; Tine et al. 1997; Nomura et al. 2007; Beck et al. 2008).

However, these line ratios may be useful for diagnosing excitation processes in extreme cases. Black & van Dishoeck (1987) note that fluorescent UV excitation of \( H_2 \) produces a significant population of vibrational levels \( v \geq 2 \) and therefore strong emission in the \( v = 2 \rightarrow 1 \) \( S(1) \) line when not thermalized in a high-density environment. This level population can be characterized by a temperature of \( T_{\text{vib}} \approx 6000–9000 \) K, much larger than the \( T_{\text{vib}} = T \approx 2000 \) K characteristic of shock excitation. Therefore any objects with observed ratios of \( H_2 \) \( v = 1 \rightarrow 0 \) \( S(1) \) to \( v = 2 \rightarrow 1 \) \( S(1) \)\( \approx 2 \) \( 2 \rightarrow 1 \) \( 0 \) \( S(1) \) \( S(1) \) \( \lesssim 0.5 \) may be exhibiting UV excited \( H_2 \) emission. However, there are no objects in our sample with \( H_2 \) \( v = 2 \rightarrow 1 \) \( 0 \) \( S(1) \) \( S(1) \) \( 0 \) \( S(1) \) \( \approx 0.25 \), so we do not have any good candidates for purely UV excitation in a dust-free environment as modeled by Black & van Dishoeck (1987).

The presence of dust grains can significantly alter these ratios and complicate their interpretation. Nomura et al. (2007) have computed the expected NIR \( H_2 \) line fluxes for conditions in circumstellar disks around young stars, modeling X-ray and UV heating in the presence of both dust and gas and accounting for thermalization at high gas densities. They find that the \( H_2 \) \( v = 2 \rightarrow 1 \) \( S(1) \) to \( v = 1 \rightarrow 0 \) \( S(1) \) line ratio is greatly impacted by the presence of dust grains of different sizes (see their Figure 17). For UV excited emission, Nomura et al. (2007) find that this line ratio is \( S(1) \) \( S(1) \) \( \approx 0.025 \) for a power law dust grain distribution with a maximum size of \( 10 \) \( \mu m \) \( mm \), roughly consistent with that expected for a protostar’s circumstellar disk. They find that the grains must be much larger (\( \sim 10 \) \( cm \) or more) for this ratio to approach the dust-free value of 0.5 computed by Gredel & Dalgarno (1995). This line ratio is much less sensitive to grain size in the case of X-ray excitation; Nomura et al. (2007) find that this value is close to the Gredel & Dalgarno (1995) value of 0.06 for a maximum grain size of \( 10 \) \( \mu m \) \( mm \). Thus they find that the \( H_2 \) \( v = 2 \rightarrow 1 \) \( S(1) \) to \( v = 1 \rightarrow 0 \) \( S(1) \) line ratio differs by only about a factor of 2 for a circumstellar disk with a power-law grain size distribution with a maximum size of \( 10 \) \( \mu m \) \( mm \). Nomura et al. (2007) do not consider collisional excitation by winds or jets, but collisional excitation may produce a fairly wide range of gas temperatures and \( H_2 \) line ratios, as discussed previously.

If excited by collisions in shocks, ratios of the \( v = 1 \rightarrow 0 \) \( S(1) \) to \( v = 1 \rightarrow 0 \) \( S(0) \) emission lines can be used to estimate ortho:para ratios of molecular hydrogen and to assess the thermal history of the emitting gas. The values of ortho:para ratios were modeled for C- and J-type shocks by Wilgenbus et al. (2000); see also their summary of previous work. Kristensen et al. (2007) and Harrison et al. (1998) showed that the \( v = 1 \rightarrow 0 \) \( S(1) \) to \( v = 1 \rightarrow 0 \) \( S(0) \) emission line ratio directly yields the molecular hydrogen ortho:para ratio with little sensitivity to \( H_2 \) rotation temperature. Using Equation (5) of Kristensen et al. (2007) and assuming \( H_2 \) rotation temperature of \( 3500 \) K, we find that the mean ortho:para ratio for our object sample is \( \langle o/p \rangle = 3.2 \pm 0.8 \). Hydrogen atom exchanges in shocks set the high temperature limit to \( o/p \leq 3 \) (e.g., see Wilgenbus et al. 2000). Thus it appears that not all objects in our sample have molecular hydrogen emission consistent with production in shocks since a number of objects have \( o/p > 3 \). Unfortunately we were unable to use line ratios to diagnose the nature of the spatially extended \( H_2 \) emissions seen in many objects (see Table 2 and Section 4.1). This emission was generally much weaker than the point source emission, and it was not detected significantly in any NIR \( H_2 \) line except \( v = 1 \rightarrow 0 \) \( S(1) \) for any object.

### 4.3. Molecular Hydrogen Excitation Mechanisms in Observed Protostars

Our sample has five objects with \( H_2 \) \( v = 2 \rightarrow 0 \) \( S(1) \) to \( v = 1 \rightarrow 0 \) \( S(1) \) line ratios in the 0.025–0.06 range, consistent with UV or X-ray excitation in the presence of dust. Of these, 04264+2433, 04295+2251, 04365+2535, and IRS 43 have relatively low mean \( H_2 \) \( v = 1 \rightarrow 0 \) \( S(1) \) line widths, FWHM \( \lesssim 15 \) \( km s^{-1} \). All but 04264+2433 have been detected in X-rays, so X-ray or UV excitation may be possible for these protostars. WL 12 is the other protostar with a line ratio in this range, and it has a broad FWHM \( \lesssim 30 \) \( km s^{-1} \) and is associated with a molecular outflow (Bontemps et al. 1996). Therefore its \( H_2 \) may be collisionally excited. However, WL 12 has ortho:para ratios of about 4.5, larger than the \( o/p \leq 3 \) limit that can be produced in C-shocks or J-shocks. The objects 04158+2805, 04181+2654, and 04181+2654 have \( H_2 \) FWHM line widths \( \gtrsim 20 \) \( km s^{-1} \) clouding a non-mechanical interpretation of their molecular hydrogen excitation.

Interestingly, there are several objects in the sample whose observed velocities and line fluxes suggest quiescent, non-mechanical origins for their molecular hydrogen emissions. 04361+2547, WL 6, and IRS 67 all have small \( H_2 \) FWHM line widths, small \( H_2 \) velocity offsets from photospheric velocities, and small \( H_2 \) emission spatial extents (see Table 2). Interestingly, at least one measurement of the \( v = 1 \rightarrow 0 \) \( S(1) \) to \( v = 2 \rightarrow 1 \) \( S(1) \) line ratios is \( \sim 0.07 \) for each object, similar to the value of 0.06 computed by Gredel & Dalgarno (1995) and Nomura et al. (2007) for X-ray excitation of \( H_2 \). Thus, these objects appear to be the best candidates for non-mechanical excitation of their molecular hydrogen emissions.

We conclude this discussion by noting that several of the protostars have \( H_2 \) ro-vibrational emission properties consistent with collisional excitation, and some others appear to be good candidates for X-ray and/or UV excitation. This is similar to the results found by Beck et al. (2008) and Bary et al. (2008) in their surveys of T Tauri stars. We also find no individual or set of spectral features that are inconsistent with previous observations of \( H_2 \) emission in CTTSs. It appears that there is no single NIR line diagnostic that can clearly identify the excitation mechanisms of \( H_2 \) in the circumstellar disks and environments of protostars, and correlations between diagnostics are not strong (Section 3.5). However, the measures of emission line morphologies, velocity widths, velocity shifts, and line ratios can constrain the various emission mechanisms when interpreted within an appropriate theoretical model.

### 5. SUMMARY

We present new observations of near-infrared \( H_2 \) line emission in a sample of 18 Class I and FS low-mass protostars, primarily in the Tau-Aur and \( \rho \) Oph dark clouds. We reach the following conclusions from analyzing these data.
1. All 17 objects found to have NIR H₂ ro-vibrational line emission spatially coincident with their continuum sources in an earlier epoch were also found to have this emission in this new study, 5–10 years later. There appears to be little temporal variation of this emission on ~1 day timescales. Ten of the 18 protostars showed H₂ v = 1–0 S(1) line emission that was over 1° in spatial extent in at least one observation (at least one position angle).

2. Nearly all of the protostars have H₂ v = 1–0 S(1) line emission radial velocities within 10 km s⁻¹ of their stellar photospheric line velocities; only three objects have H₂ velocity offsets greater than or equal to 10 km s⁻¹. This evidence suggests that collisional excitation in jets is unlikely to be the molecular hydrogen excitation mechanism in many objects.

3. The H₂ v = 1–0 S(1) line FWHM line widths of all 17 protostars with this feature on-source are broader than 10 km s⁻¹ (Figure 3). Six of the emitting objects (35%) exhibit FWHM greater that 20 km s⁻¹, and these are good candidates for collisional excitation in jets or winds. Seven of the emitting objects (41%) have point source FWHM line widths below 16 km s⁻¹. The spatially extended H₂ v = 1–0 S(1) line emission of two objects had FWHM line widths ≥40 km s⁻¹, about twice that of their central point source emission. This is consistent with collisional excitation by jets or winds.

4. The molecular hydrogen emission line velocities and FWHM values of at least 3–6 of the 17 objects with on-source emission are consistent with collisional excitation in jets. At least seven or eight objects have H₂ velocity parameters consistent with quiescent (non-collisional) excitation. There are several objects whose small emission line widths, small H₂ photospheric radial velocity differences, and small spatial extents are more consistent with quiescent molecular hydrogen emission and not collisional excitation.

5. Several of the protostars have H₂ v = 2–0 S(1) line ratio indicative of X-ray or UV excitation (in the presence of dust) and are known X-ray emitters. 04361+2547, WL 6, and IRS 67 are the best examples of such protostars. However, we see no rapid variation in the H₂ Δv = 1 S(1) line fluxes on ~24 hr timescales as might be expected from excitation by X-ray flaring events.

6. We find that the mean ortho:para ratio for our object sample is (o/p) = 3.2 ± 0.8. Hydrogen atom exchanges in shocks set the high temperature limit to o/p ≤ 3 (e.g., see Wilgenbus et al. 2000). Thus it appears that not all objects in our sample have molecular hydrogen emission consistent with production in shocks since a number of objects have o/p > 3. 04158+2805, 04181+2654, WL 6, and WL 12 are all estimated to have ortho:para ratios significantly higher than this value. However, WL 6 is the only protostar with H₂ line ratios and velocities also indicative of non-mechanical excitation.

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