Detection of $\text{H}_2$ in the TWA 7 System: A Probable Circumstellar Origin

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Abstract

Using HST–COS far-UV spectra, we have discovered warm molecular hydrogen in the TWA 7 system. TWA 7, a $\sim$9 Myr old M2.5 star, has a cold debris disk and has previously shown no signs of accretion. Molecular hydrogen is expected to be extremely rare in a debris disk. While molecular hydrogen can be produced in starspots or the lower chromospheres of cool stars such as TWA 7, fluxes from progressions that get pumped by the wings of Ly$\alpha$ indicate that this molecular hydrogen could be circumstellar and thus that TWA 7 is accreting at very low levels and may retain a reservoir of gas in the near circumstellar environment.

Unified Astronomy Thesaurus concepts: Protoplanetary disks (1300); Debris disks (363); T Tauri stars (1681); Planet formation (1241); High resolution spectroscopy (2096); Ultraviolet astronomy (1736); Circumstellar gas (238)

1. Introduction

Planet formation and evolution are heavily dependent on the circumstellar environment. The circumstellar material can dictate formation, composition, orbital parameters, and migration of planets. While much has been learned in recent years about circumstellar disks, especially with the Atacama Large Millimeter/submillimeter Array (ALMA, Andrews et al. 2018), the evolution from protoplanetary disk to debris disk is not well understood. This time period is crucial for the final stages of the growth of terrestrial planets and the early evolution of their atmospheres (e.g., Kenyon & Bromley 2006; Olson & Sharp 2019). Additionally, ALMA typically images only the outer regions of disks; it is also of interest to understand the inner few au of a system where many exoplanets are found and where the systems’ habitable zones are.

Protoplanetary disks consist of gas, dust, and eventually planetesimals. All three components play a crucial role in the formation and evolution of planets. Measurements of micron-sized dust are relatively easy, as dust can produce detectable amounts of infrared (IR) emission, even through the debris disk stage. However, the primordial gas, which is mostly molecular hydrogen, is assumed to be 99% of the protoplanetary disk mass (see review by Williams & Cieza 2011) and controls much of the disk dynamics, such as altering orbits of planetesimals and planets (e.g., Weidenschilling 1977; Goldreich & Sari 2003; Youdin & Goodman 2005; Baruteau et al. 2014) and potentially producing rings and spirals (Lyra & Kuchner 2013; Gonzalez et al. 2017). Lower gas fractions and optically thin gas are expected in debris disks (Wyatt 2008), although the precise gas fraction is poorly constrained (Matthews et al. 2014) and possibly varies significantly between disks. But even small amounts of optically thin gas can still have a large effect on disk dynamics (e.g., Takeuchi & Artymowicz 2001; Lyra & Kuchner 2013). Thus, to understand the evolution of the circumstellar environment, we must understand how the hydrogen evolves.

However, $\text{H}_2$ is notoriously hard to detect. Its only allowed electric dipole transitions are in the ultraviolet (UV). In most circumstellar environments, those transitions require excited $\text{H}_2$, which can occur in circumstellar disks with warm gas (Nomura & Millar 2005; Adámkovics et al. 2016). Warm gas is common in protoplanetary disks, but is less likely to be found in debris disks because of the generally large distance of the gas from the central star. Chromospheric and transition region lines, such as Ly$\alpha$, pump the $\text{H}_2$ molecule from an excited level in the ground electronic state to the first (Lyman) or second (Werner) electronic levels. Because of extremely high oscillator strengths, the excited molecule immediately decays back to the ground electronic level in a fluorescent cascade, emitting photons. The set of emission lines produced by transitions from a single excited electronic state to the multiple allowed ground electronic states is called a progression. Within a given progression, $\text{H}_2$ line fluxes are proportional to their branching ratios (Wood et al. 2002; Herczeg et al. 2004). Because of this, far-UV spectra are a powerful way to characterize the warm $\text{H}_2$ gas. Emission from these lines is a probe of gas temperature. But as all these transitions are in the UV, they require data from space-based observatories, thus limiting the number of observations currently available. There are magnetic transitions in the IR that have been detected in protoplanetary disks (e.g., Weintraub et al. 2000; Bary et al. 2003); unfortunately, they are weak and require much larger amounts of warm $\text{H}_2$ than debris disks typically have in order for us to detect them (e.g., Binet et al. 2008; Carmona et al. 2008).

To try to get around these issues, other molecules, most notably IR and millimeter transitions of HD and more commonly CO, have been used to trace the $\text{H}_2$ (e.g., Trapman et al. 2017). However, neither is a perfect tracer, and both rely on an assumed ratio to $\text{H}_2$. For example, estimates of disk mass have often used the CO/$\text{H}_2$ ratio in the interstellar medium (ISM) of $\sim10^{-4}$, consistent with the value found by France et al. (2014) based on CO and $\text{H}_2$ observations in the UV, but other recent studies have shown that CO appears depleted in protoplanetary disks (Favre et al. 2013; McClure 2019;
Schwarz et al. 2019). Furthermore, the differences in chemistry and masses between the molecular species mean that neither HD nor especially CO traces H$_2$ perfectly (Molyarova et al. 2017; Aikawa et al. 2018).

Molecular hydrogen emission has been detected in every protoplanetary and transition disk that has far-UV spectral observations (e.g., Valenti et al. 2000; Ardila et al. 2002; Herczeg et al. 2006; Ingleby et al. 2009; France et al. 2012, 2017; Yang et al. 2012). Debris disks are not defined by their gas content—they are instead defined by secondary dust produced from planetesimal collisions, which observationally gets translated into a fractional luminosity, $f = L_{\text{disk}}/L_\star$ less than $10^{-2}$—but all evidence indicates that, compared with protoplanetary disks, they have a smaller gas-to-dust ratio and less gas in total (e.g., Chen et al. 2007). Other gas species, such as CO, have been detected in debris disks (e.g., Roberge & Weinberger 2008; Moór et al. 2011; Dent et al. 2014; Higuchi et al. 2017), but the only previous potential detection of H$_2$ in what is clearly a debris disk is from AU Mic (France et al. 2007). This is not unexpected. While comets in our own solar system produce CO, they do not produce H$_2$ (Mumma & Charnley 2011). Thus, it is likely that secondary H$_2$ is not produced in the same manner as secondary CO. In several cases, there are arguments for the reclassification of systems based on the discovery of H$_2$, such as RECX 11 (Ingleby et al. 2011a), HD 98800 B (TWA 4 B) (Yang et al. 2012; Ribas et al. 2018), and potentially DoAr 21 (Bary et al. 2003; Jensen et al. 2009). But exactly when and on what timescale the H$_2$ dissipates is not known.

Since even small amounts of H$_2$ gas can have a significant impact on planetary systems at ages $\sim 10$ Myr, we have begun a program to examine UV spectra of young stars that show no evidence of near-infrared (NIR) excess. One specific way that gas can impact a system is by limiting the IR flux from dust produced by planetesimal collisions. Kenyon et al. (2016) show that there is a discrepancy between the incidence rate of dust expected to be produced by terrestrial planet formation (2%–3% of young systems) and the incidence rate of close-in terrestrial planets (20% of mature systems). Gas, however, could sweep away that dust via gas drag, making it harder to detect. Thus, it is critical to understand the evolution of H$_2$ in the terrestrial planet-forming regions.

2. Target and Observations

TWA 7 is an M dwarf that is part of the $\sim 7$–10 Myr TW Hya Association (Webb et al. 1999). Recent spectral classifications assign an M2 or M3 spectral type (Manara et al. 2013; Herczeg & Hillenbrand 2014); we adopt M2.5. The star is surrounded by a debris disk that was first detected due to its IR excess at 24 and 70 $\mu$m by Low et al. (2005) with the Spitzer Space Telescope. However, the lack of near IR excess (Weinberger et al. 2004) and typical accretion signatures (Jayawardhana et al. 2006) strongly imply that it is a “cool” debris disk, making it one of the few known M stars with a debris disk (Theissen & West 2014). The dust in the disk has since been detected in the far IR at 450 and 850 $\mu$m using the James Clerk Maxwell Telescope (Matthews et al. 2007) and at 70, 160, 250, and 350 $\mu$m using the Herschel Space Observatory (Cieza et al. 2013). No [O I] was detected by Herschel at 63 $\mu$m (Riviere-Marichalar et al. 2013), but CO has recently been detected using ALMA in the $J = 3$–2 transition (Matrà et al. 2019). The disk has been imaged in the IR with SPHERE, showing spiral arms near 25 au (Olofsson et al. 2018). Yang et al. (2012) and France et al. (2012) both failed to detect H$_2$ around TWA 7 in UV spectra. Yang et al. (2012) used a less sensitive prism spectrum; France et al. (2012) looked at 12 H$_2$ features separately, as opposed to detecting the combined H$_2$ emission from many features as we do in this paper. (See Section 3.1.)

We can put some constraints on the expected H$_2$ based on dust and CO measurements. For TWA 7, the total dust mass in the disk, $M_{\text{d}}$, is $2 \times 10^{-2} M_\odot$ (Bayo et al. 2019), while the mass of CO in the disk, $M_{\text{CO}}$, is 0.8–80 $\times 10^{-6} M_\odot$ (Matrà et al. 2019). Based on these estimates, if TWA 7 has an ISM value for the CO/H$_2$ ratio of $\sim 10^{-4}$ then we can expect $M_{\text{H_2}}$ to be of the order of $M_\odot$. If it has a lower CO/H$_2$ of $\sim 10^{-6}$, as TW Hya has (Favre et al. 2013), we can expect $M_{\text{H_2}}$ to be 100 times smaller than $M_\odot$, consistent with the ISM gas-to-dust ratio (Spitzer 1978). Models that have explored gas-to-dust ratios between 0.01 and 100 indicate that gas can significantly influence the disk dynamics (Youdin & Goodman 2005; Lyra & Kuchner 2013; Gonzalez et al. 2017), so in either case, H$_2$ could play an important if not dominant role in TWA 7’s disk dynamics. Given the presence of this distant reservoir of gas, we explore here the possibility that an (as yet unseen) reservoir of gas is also present at smaller disk radii, in the terrestrial planet region of the disk.

For this work, we used archival Hubble Space Telescope (HST)–Cosmic Origins Spectrograph (COS) observations of TWA 7 from 2011 May (PID 11616, PI: G. Herczeg). The data were acquired with the far-UV medium-resolution modes of COS: G130M and G160M. These spectra have a spatial resolution of 1″ and a wavelength uncertainty of $\sim 15$ km s$^{-1}$ (Dashtamirova et al. 2020). The observations are at a range of central wavelengths that allow us to get a contiguous spectrum that spans from 1133 to 1795 Å (Figure 1). In addition to TWA 7, we also analyze spectra of classical T Tauri stars (CTTS) and main-sequence M dwarf stars for comparison purposes (Table 1) taken between 2009 December and 2015 August. The CTTS were chosen from the stars analyzed by France et al. (2012) that had extinction values measured by both Herczeg & Hillenbrand (2014) and Furlan et al. (2011). The main-sequence M dwarfs were from Kruczek et al. (2017), chosen because they had H$_2$ detected from the stellar photosphere and COS spectra that covered a comparable wavelength range. One of the six M dwarfs —GJ 581—has a cold, faint debris disk (Lestrade et al. 2012), but it is much older (2–8 Gyr) and less active (Schöfer et al. 2019) than TWA 7 or the CTTS. Its disk is also significantly less luminous than that of TWA 7 (Choquet et al. 2016). The remaining five M dwarfs have no detected disks. All spectra were observed with COS in a similar manner. Spectra were reduced by the CALCOS pipeline. Multiple observations were then coadded into one spectrum as described by Danforth et al. (2016). The TWA 7 spectrum we analyzed is plotted in Figure 1.

We also used archival HST–Space Telescope Imaging Spectrograph (STIS) spectra of TW Hya, reduced with the STIS pipeline. For each observation, we combined the orders to create a single spectrum. We then coadded the observations in a similar manner to the way we coadded the observations from COS.

3. Analysis and Results

3.1. Methods for Cross-correlation

In protoplanetary disks and nearby M dwarfs, the strength of the H$_2$ lines makes them clearly detectable above the noise; however, this is not the case for systems with smaller amounts of H$_2$ flux. Instead, we take advantage of the many weak H$_2$
lines in the system and use a cross-correlation function (CCF), a technique that has been used previously with IR data to study gas in protoplanetary disks (Hartmann & Kenyon 1987). The CCF allows us to combine the signal from multiple lines into one signal by calculating how well the spectrum correlates with that of a model template (Tonry & Davis 1979). Our full template was created using the procedure from McJunkin et al. (2016) for a temperature of 2500 K and a column density of \( \log(N(H_2)) = 19 \), where \( N \) is in units of \( \text{cm}^{-2} \). As temperature and density have little effect on the relative strengths of these lines in protoplanetary disks (France et al. 2012), we used the same template for all the stars. Ly\( \alpha \) also has a significant

### Table 1

| Object   | PID/PI        | Distance (pc) | RV (km s\(^{-1}\)) | \( A_v^a \) (mag) | \( A_v^b \) (mag) |
|----------|---------------|---------------|---------------------|-------------------|-------------------|
| TWA 7    | 11616/Herczeg | 34.0          | 11.4                | ...               | 0.00\(^c\)        |
| **Classical T Tauri stars** | | | | | |
| AA Tau   | 11616/Herczeg | 136.7         | 17.0                | 1.9               | 0.40              |
| BP Tau   | 12036/Green   | 128.6         | 15.2                | 1.0               | 0.45              |
| DE Tau   | 11616/Herczeg | 126.9         | 15.4                | 0.9               | 0.35              |
| DM Tau   | 11616/Herczeg | 144.5         | 18.6                | 0.0               | 0.10              |
| DR Tau   | 11616/Herczeg | 194.6         | 21.1                | 1.4               | 0.45              |
| GM Aur   | 11616/Herczeg | 159.0         | 15.2                | 0.6               | 0.30              |
| HN Tau   | 11616/Herczeg | 136.1         | 4.6                 | 1.0               | 1.15              |
| LkCa 15  | 11616/Herczeg | 158.2         | 17.7                | 1.0               | 0.30              |
| SU Aur   | 11616/Herczeg | 157.7         | 14.3                | 0.9               | 0.65              |
| UX Tau   | 11616/Herczeg | 139.4         | 15.5                | 0.5               | 0.00\(^c\)        |
| **Main-sequence M stars with H\(_2\)** | | | | | |
| GJ 176   | 13650/France  | 9.5           | 26.2                | ...               | ...               |
| GJ 832   | 12464/France  | 5.0           | 13.2                | ...               | ...               |
| GJ 667 C | 13650/France  | 7.2           | 6.4                 | ...               | ...               |
| GJ 436   | 13650/France  | 9.8           | 9.6                 | ...               | ...               |
| GJ 581   | 13650/France  | 6.3           | −9.4                | ...               | ...               |
| GJ 876   | 12464/France  | 4.7           | −1.6                | ...               | ...               |
| **STIS spectra** | | | | | |
| TW Hya   | 11608/Calvet  | 60.1          | 13.4                | ...               | 0.00              |

**Notes.** Properties of stars analyzed in this paper. Distances are from Bailer-Jones et al. (2018) based on Gaia DR2 Collaboration et al. (2018). Radial velocities (RVS) are from Nguyen et al. (2012) for the T Tauri stars, from Gaia DR2 for the M stars, and from Torres et al. (2006) for TW Hya and TWA 7. Based on extinction measurements from stars in the Local Bubble (Leroy 1993), we assume these main-sequence M stars have no extinction.

\(^a\) \( A_v \) from Furlan et al. (2011).

\(^b\) \( A_v \) from Herczeg & Hillenbrand (2014) with uncertainties of 0.15 mag.

\(^c\) The measured value was negative. Since this is unphysical, we adopted an extinction of 0.0 mag.
impact on H$_2$ line strengths, but its profile is contaminated by self-absorption, ISM absorption, and geocoronal airglow, and thus cannot be used for all of our targets. As a result, we do not consider the shape of the Ly$\alpha$ profile when defining our template. We use a single FWHM of 0.047 Å for the lines in the template, chosen solely because it is the width that maximizes the CCF for TWA 7. Templates for individual progressions were created by picking the lines from the full template based on Abgrall et al. (1993) (Figure 2). Although there are many H$_2$ lines, focusing only on the strongest lines gives the clearest signal. We chose the minimum H$_2$ line strength in the template that maximized the CCF detection for TWA 7 for each progression. The minimum line strength is dependent on how strong the lines in that progression are: progressions with weaker fluxes require smaller minimum line strengths. While we analyzed 12 different progressions (Table 2), chosen because all 12 were detected by France et al. (2012) in protoplanetary disks, our analysis focused on the progressions that typically produce the most H$_2$ flux in CTTS—[1, 4], [1, 7], [0, 1], and [0, 2]. Each of these progressions is excited by Ly$\alpha$ and can decay to multiple lower states, resulting in a set of H$_2$ emission lines throughout the UV. The total summed flux in an individual progression is a function of having enough Ly$\alpha$ photons to pump the H$_2$ molecule to the excited state (Figure 3), the filling factor of H$_2$ around the Ly$\alpha$, the column density in the excited rovibrational level of the X electronic state, and the oscillator strength of the pump transition (Herczeg et al. 2006).

Since we want to be sure that we are only cross-correlating continuum and H$_2$ emission (plus the associated noise) and not emission from hot gas lines from the chromosphere or transition region, we masked out far-UV (FUV) lines commonly seen in lower-mass stars from Herczeg et al. (2002), Brandt et al. (2001), and Ayres (2015). These lines have different widths in different stars depending on numerous properties, so we erred on the side of masking the wavelength regions covered by the broadest of these features to minimize the chance of a false positive from a line that was not H$_2$.

Cross-correlating the entire spectrum with the entire masked template returns a tentative detection. However, this involves cross-correlating a significant amount of noise, which can weaken the detection. Therefore we created segments of spectrum for each H$_2$ feature of $\sim$1 Å ($\sim$200 km s$^{-1}$) wide centered around the wavelengths of expected H$_2$ lines, which is

### Table 2

| Frequency (Å) | Velocity (km s$^{-1}$) | TW Hya H$_2$ Flux ($10^{-15}$ erg cm$^{-2}$ s$^{-1}$) | Oscillator Strength ($\times 10^{-3}$) | [v$^0$, j$'$] | E$^\circ$ (eV) |
|--------------|------------------------|-------------------------------------------------|--------------------------------------|--------------|--------------|
| 1213.356     | -571                   | 4.7                                             | 20.6                                 | [1, 14]      | 1.79         |
| 1213.677     | -491                   | 2.4                                             | 9.33                                 | [2, 12]      | 1.93         |
| 1214.465     | -297                   | 14.9                                            | 23.6                                 | [1, 15]      | 1.94         |
| 1214.781     | -219                   | 8.9                                             | 9.90                                 | [3, 5]       | 1.65         |
| 1215.726     | 14                     | 16.2                                            | 34.8                                 | [2, 6]       | 1.27         |
| 1216.670     | 99                     | 36.0                                            | 28.9                                 | [2, 5]       | 1.20         |
| 1217.038     | 338                    | 3.5                                             | 1.28                                 | [3, 1]       | 1.50         |
| 1217.205     | 379                    | 37.9                                            | 44.0                                 | [2, 9]       | 1.00         |
| 1217.643     | 487                    | 33.4                                            | 28.9                                 | [2, 11]      | 1.02         |
| 1217.904     | 551                    | 18.4                                            | 19.2                                 | [1, 13]      | 1.64         |
| 1218.521     | 704                    | 3.1                                             | 18.0                                 | [1, 14]      | 1.79         |
| 1219.089     | 844                    | 2.1                                             | 25.5                                 | [2, 2]       | 1.04         |

**Notes.** Velocity is from Ly$\alpha$ center. TW Hya H$_2$ flux as measured by Herczeg et al. (2006). Oscillator strengths of the pumping transitions calculated by Herczeg et al. (2006) based on Abgrall et al. (1993). [v$^0$, j$'$] and E$^\circ$ are the lower level in the electronic ground state for the pumping transition and the corresponding energy for that state. Each of these progressions is pumped by Ly$\alpha$ flux and can decay to multiple lower states, resulting in a set of H$_2$ emission lines throughout the UV.
wide enough to get the entire line profile without adding too much continuum flux or noise. (We cannot be certain whether the photons detected outside of lines are from the star itself, because M dwarfs have very little stellar continuum flux in these regions, so we will refer to the region outside of lines as “continuum/noise.”) To calculate the final CCF, we explored two procedures to verify any findings. With both methods, if the flux for every line is emitted at a similar relative velocity (within $\sim 10$ km s$^{-1}$), the CCF’s signal will grow stronger. In the first method, we created one long spectrum by placing all the individual segments end-to-end. We did the same for the corresponding template segments. We then cross-correlated this pieced together spectrum with the same regions from the template. In the second method, we cross-correlated each segment of spectrum individually with its corresponding template segment and added the cross-correlation functions. Because of this, we chose to use a CCF that has not been normalized for length, which is usually the last step of calculating the CCF. Unnormalized CCFs work equally well for both of our methods; normalized CCFs of different lengths cannot be added linearly, because longer CCFs should be weighted more.

### 3.2. H$_2$ Detection and Verification

We detect peaks near the stellar radial velocity in the CCFs of the spectra of TWA 7 (Figure 4) using a minimum H$_2$ template line strength cutoff of $5 \times 10^{-15}$ erg s$^{-1}$ cm$^{-2}$ Å$^{-1}$. The peaks are detected with both methods—segmented spectrum and added CCF—for calculating the CCF. Although the peak is strongest when all of the most prominent progressions are included, we also see significant ($>3\sigma$) detections when some individual progressions are analyzed. While the peak for $[0, 1] + [0, 2]$ is slightly off-center from the systemic velocity of 11.4 km s$^{-1}$, we attribute this to the uncertainties in the wavelength calibration that can lead to shifts in the resulting velocities by up to 15 km s$^{-1}$, as described in Linsky et al. (2012).

The strength of the cross-correlation function is dependent on the signal-to-noise ratio in the H$_2$ lines. Since we are trying to measure the height and significance of the CCF peak, we need to understand the noise properties of the observed spectrum. This is made more difficult, because there are so few FUV photons that reach us. For example, Loyd et al. (2016) looked for FUV continuum in our sample of M dwarfs, obtaining a significant detection for only three of six targets. As a result, noise in our spectrum cannot be approximated as Gaussian, as it can when there are hundreds or thousands of counts. Typical continuum/noise regions in our TWA 7 spectrum have flux distributions that look approximately like that seen in Figure 5, where we show a histogram of flux levels found in the continuum/noise of TWA 7.

There are several potential issues in modeling this noise. The first is that there are undoubtedly unidentified lines that we do not mask, as possibly seen in the increase around $0.3 \times 10^{-15}$ erg s$^{-1}$ cm$^{-2}$ Å$^{-1}$. However, since other unidentified lines could possibly overlap with the H$_2$ lines, we choose not to remove this peak from the distribution. Another issue is that because of the low flux level, when the detector background gets subtracted, we end up measuring “negative” flux in some wavelength bins. To deal with this, we estimate the noise in two separate ways: with a scaled Poisson distribution and using the actual distribution fit with a kernel density estimator (KDE) (Rosenblatt 1956; Parzen 1962), as shown in Figure 5. The scaled Poisson was determined by calculating the skew of the distribution of continuum/noise, $\gamma_1$. The mean of the Poisson distribution $\lambda$ is then $\gamma_1^{\lambda}$. We then convert from counts to flux using a constant scaling factor determined by the mean of the distribution. The KDE was calculated with a Gaussian kernel using a bandwidth (equivalent to the sigma parameter) of $10^{-17}$ erg s$^{-1}$ cm$^{-2}$ Å$^{-1}$. We randomly draw our noise from these distributions. These two noise models cover the range of possibilities of the underlying true noise, so a robust detection will only be evident if it occurs using both noise models.

To determine the significance of the detection, we used our noise models to create spectra containing only noise. We then cross-correlated these noise spectra with the template in the same way we did for the TWA 7 spectrum. We then record the CCF maximum within 15 km s$^{-1}$ of the systemic velocity. We chose this range because it was the range we used to look for a detection, as COS has a velocity precision of 15 km s$^{-1}$. This
procedure was repeated multiple times (see Table 3) for each type of noise to produce the distributions shown in Figure 6. We then compared the CCF maxima to TWA 7’s CCF maximum within 15 km s\(^{-1}\) of the systemic velocity. The fraction of times the noise’s CCF maximum was equal to or larger than TWA 7’s CCF maximum is taken to be the probability of a false positive. The significance (\(\sigma\)) values we report are the equivalent probabilities for a Gaussian distribution.

We did an initial trial of 32,000 simulations with each method to see whether we could detect each progression individually. We obtain significant detections for \([0, 1]\), \([0, 2]\), \([1, 4]\), and \([1, 7]\), with significant being defined as \(>3\sigma\) detections for all four methods; we also get a marginal detection (\(>3\sigma\) for some but not all methods) for \([0, 3]\) (Table 3). We then investigated the detected progressions further. Using a line strength cutoff of \(5 \times 10^{-15}\) erg s\(^{-1}\) cm\(^{-2}\) Å\(^{-1}\), as shown in Figure 2, we detect H\(_2\) at a significance \(>5\sigma\) for all of our noise models and CCF types for the combination of the \([1, 4]\), \([1, 7]\), \([0, 1]\), and \([0, 2]\) progressions based on 3,500,000 simulations of each. For just the progressions on the wing—\([0, 1]\) combined with \([0, 2]\)—we did 1,200,000 simulations for each measurement. We detect H\(_2\) at a level of 4.5\(\sigma\) for Poisson noise with the added CCFs, 4.6\(\sigma\) for KDE noise with the added CCFs, 3.9\(\sigma\) for Poisson noise with the segmented spectrum CCF, and 4.0\(\sigma\) for KDE-sampled noise with the segmented spectrum CCF. The segmented spectrum CCF produces similar distributions for both types of noise, as

**Figure 4.** Cross-correlation functions of TWA 7 for the most prominent H\(_2\) progressions.

**Figure 5.** Typical continuum/noise distributions, which we model in two ways: by creating a KDE of the distribution and by scaling a discrete Poisson distribution to the data. Both were normalized so that the total area is equal to 1.
shown on the right of Figure 6, because it is more robust to slight
differences in noise models.

There are two unclassified background objects in the sky
near TWA 7. However, the two sources are not expected to be
in the COS–Primary Science Aperture, given its size of 2″5 in
diameter and the distance of the background sources to TWA 7,
at 2″5 (Neuhäuser et al. 2000) and 6″ (Bayo et al. 2019),
given that we confirmed that TWA 7 was centered on the aperture.
Furthermore, as we required that the CCF peak at the radial
velocity of the object fall within the error of the spectrograph,
we feel these background sources are an extremely unlikely
source of the H2.

### 3.3. Determining the Origin of the H2

Simply detecting H2 does not indicate that the H2 is
circumstellar in origin, because some M stars are known to
show H2 emission pumped by Lyα (Kruczek et al. 2017).
Active M stars, such as TWA 7 (Yang et al. 2008), have strong
cromospheric Lyα emission, which can pump H2 in starspots
or in their lower chromospheres. Since TWA 7’s debris disk is
nearly face-on at an inclination of 13° (Olofsson et al. 2018),
and the resolution of COS is 15 km s−1, we cannot use velocity
information to differentiate between circumstellar and stellar
H2. Instead, we looked at the flux ratios between different
progressions. The [1, 4] and [1, 7] progressions are both
pumped by emission from the center of the Lyα line profile
(Figure 3). Other progressions are pumped from the wings of
the profile, so strong emission in these lines is only possible
with a broader Lyα line indicative of active accretion. The two
most prominent examples are [0, 1] and [0, 2], which are
pumped at velocities of 379 and 487 km s−1 from line center.
These progressions should only be bright if the Lyα profile is
especially wide, as shown in the purple profile in Figure 3,
but they will be much fainter if the star’s Lyα profile is narrower,
similar to the pink curve. Stars that are accreting have much
broader Lyα profiles than active main-sequence stars (Schind-
helm et al. 2012; Youngblood et al. 2016) and are therefore

![Figure 6. Distribution of CCF heights for simulations of noise cross-correlated with the [0, 1] and [0, 2] progressions of the H2 template. Based on 1,200,000 simulations for each set, we detect H2 at a level of 4.5σ for Poisson noise with the added CCFs, 4.6σ for KDE-sampled noise with the added CCFs, 3.9σ for Poisson noise with the segmented spectrum CCF, and 4.0σ for KDE-sampled noise with the segmented spectrum CCF.](image)

### Table 3

Detection Significance of H2 in Progressions

| Progression | Added CCF | Segmented Spectrum CCF | Simulations | Minimum Line Strength (erg s⁻¹ cm⁻²Å⁻¹) | Lines Included |
|-------------|-----------|------------------------|------------|------------------------------------------|---------------|
| [3, 13]     | 2.2       | 1.6                    | 32,000     | 0.1 × 10⁻¹⁵                              | 9             |
| [4, 13]     | 0.7       | 0.8                    | 32,000     | 1.7 × 10⁻¹⁵                              | 2             |
| [3, 16]     | 2.4       | 1.8                    | 32,000     | 1.2 × 10⁻¹⁵                              | 9             |
| [4, 4]      | 1.2       | 2.0                    | 32,000     | 1.3 × 10⁻¹⁵                              | 6             |
| [1, 7]      | >4.0      | >4.0                   | 32,000     | 7.5 × 10⁻¹⁵                              | 2             |
| [1, 4]      | >4.0      | >4.0                   | 32,000     | 3.0 × 10⁻¹⁵                              | 12            |
| [3, 0]      | 0.7       | 0.0                    | 32,000     | 3.5 × 10⁻¹⁵                              | 2             |
| [0, 1]      | 3.5       | 3.2                    | 32,000     | 9.0 × 10⁻¹⁵                              | 2             |
| [0, 2]      | >4.0      | 3.3                    | 32,000     | 5.0 × 10⁻¹⁵                              | 2             |
| [2, 12]     | 2.2       | 2.6                    | 32,000     | 2.0 × 10⁻¹⁵                              | 2             |
| [2, 15]     | 2.8       | 2.7                    | 32,000     | 3.0 × 10⁻¹⁵                              | 4             |
| [0, 3]      | 3.3       | 2.9                    | 32,000     | 3.0 × 10⁻¹⁵                              | 5             |
| [0, 1] + [0, 2] | 4.6   | 4.0                    | 3,500,000  | 5.0 × 10⁻¹⁵                              | 6             |
| [1, 4] + [1, 7] + [0, 1] + [0, 2] | >5.0 | >5.0                   | 3,500,000  | 5.0 × 10⁻¹⁵                              | 20            |

**Note.** Significance of detection in each individual progression for our four different methods, as well as for the combination of [0, 1] and [0, 2] and the combination of [1, 4], [1, 7], [0, 1], and [0, 2].
expected to produce more emission in the [0, 1] and [0, 2] progressions relative to the [1, 4] and [1, 7] progressions than non-accretors.

Using the segmented spectrum, we took the ratio of the CCF maximum of all the non-central progressions to the ratio of the CCF maximum of [1, 4] + [1, 7] for all the stars with previously detected H2 in our sample. Dividing by the height of [1, 4] + [1, 7] for each system acts as a normalization factor to deal with spectra with different signal-to-noise ratios or different line widths due to rotational broadening. Since this ratio can be affected by extinction, with lines at shorter wavelengths appearing fainter than they are intrinsically, we have to de-redden the spectrum first, which we do based on the extinction laws from Cardelli et al. (1989). We examine three different sets of ratios: ratios with spectra uncorrected for extinction, ratios with spectra corrected by the extinction values found by Furlan et al. (2011), and ratios with spectra corrected by extinction values from Herczeg & Hillenbrand (2014). We assume that the main-sequence M stars and TWA 7 have no extinction based on extinction measurements from stars in the Local Bubble (Leroy 1993).

To estimate the 1σ limits (the gray areas in Figures 7 and A1), we used a similar procedure to what we used to calculate the significance of detections for TWA 7. We sampled the noise from each spectrum, calculating a KDE like we did for TWA 7, and created spectra of pure noise to cross-correlate with the template. We then took the maximum of each CCF within 15 km s⁻¹ of the RV of that star. The gray regions represent the inner 68% of ratios calculated based on those maxima. These 1σ regions are biased toward positive numbers, because we chose the maximum CCF value, which even in a normally distributed, random noise sample will bias to positive values.

The [0, 1] and [0, 2] ratios differentiate the samples most clearly regardless of extinction correction. Based on their data, TWA 7’s H2 appears to be more similar to that from the CTTS (Figure 7). However, other progressions are not as clear. To analyze all of the ratios, we created a support vector machine classifier (Platt 1999) with a fourth-order polynomial kernel using the data from the M dwarfs and CTTS—excluding TWA 7—to determine where the H2 was coming from. We then applied this classification scheme to the TWA 7 data. Based on the observed ratios, this test categorizes TWA 7’s H2 as similar to CTTS’ 99.2% of the time for the set uncorrected for extinction, 98.2% of the time for the set corrected using the extinction values from Herczeg & Hillenbrand (2014), and 98.3% of the time for the set corrected using the extinction values from Furlan et al. (2011). This implies that TWA 7’s H2 is being pumped not only from the core but also from the wings of the Lyα profile, as with CTTS. We expand upon this in Section 4.

3.4. Estimating the Amount of Circumstellar H2

To estimate the amount of warm H2 in TWA 7, we compared its H2 emission with that of a transition disk system, TW Hya. We chose TW Hya because in comparison with TWA 7, it has a similar age (Webb et al. 1999), inclination (Pontoppidan et al. 2008), and a relatively similar spectral type (Herczeg & Hillenbrand 2014). While we do not think that the line profile of TW Hya would be identical to that of TWA 7, as TW Hya is accreting enough to be measured by conventional methods, it is the best match from the data available. Our goal was to find a constant scale factor that is the ratio between the H2 line strengths in TWA 7 and those in TW Hya. We used a least-squares fit to calculate this scale factor with the only other free parameter being the difference in radial velocity. We coadded the 19 brightest H2 features from the most prominent progressions—[1, 4], [1, 7], [0, 1], and [0, 2]—and compared the line flux from the coadded profile to the coadded profile from TW Hya. We also measured the uncertainty of this ratio by measuring the noise in the spectrum in comparison to the flux. We found a ratio between the coadded profiles of (6.9 ± 0.7) × 10⁻⁴, as shown in Figure 8. Adjusting for differences in distance, TWA 7 has (2.2 ± 0.2) × 10⁻⁴ of TW Hya’s H2 line strength, and, as a result of its similar inclination and line widths, its H2 luminosity is assumed to be less than TW Hya’s by the same factor. France et al. (2012) measure TW Hya’s H2 luminosity as (16.2 ± 2.0) × 10²⁹ erg s⁻¹. This gives us an H2 luminosity of (3.6 ± 0.6) × 10²⁶ erg s⁻¹ for TWA 7. By comparing the flux values measured by Krueckel et al. (2017) in starspots to our value for TWA 7’s flux, even if there is a contribution from starspots to this value, we expect that the circumstellar gas represents more than 50% of the total H2 luminosity.

From this scaling factor, we can also put a lower limit on the mass of warm H2, assuming the gas is all circumstellar. The flux observed in a specific H2 line, $F_{\text{obs}}$, is a function of the Einstein A-value for that emitting transition, $A_{\text{eff}}$, the distance to TWA 7, $d$, the frequency of the emitting transition, $\nu_{\text{H2}}$, and the number of H2 molecules that have been pumped to the required
We calculate $q(T)N_{H_2} = N_X$, where $N_{H_2}$ is the number of $H_2$ molecules in the lower state, $N_X$ is the frequency of the pumping transition, and $q(T)$ is the ratio of the pumping transition to the wings. We then average these values together to get our final result. For a gas temperature of 1500 K, we get a rough estimate for the minimum amount of warm $H_2$ of $9.9 \times 10^{-11} M_\odot$. If spread out in a ring with a radius of 0.3 au—a radius at which $H_2$ is commonly seen (France et al. 2012)—this corresponds to a minimum column density of $\sim 2.8 \times 10^{15} \text{ cm}^{-2}$. This is consistent with the upper limit on $H_2$ column density reported by Ingleby et al. (2009) of $3.0 \times 10^{17} \text{ cm}^{-2}$ using a less sensitive prism spectrum of TWA 7. Based on the spread of line fluxes, we adopt a range of $10^{15}$ to $3.0 \times 10^{17} \text{ cm}^{-2}$ for the vertical column density of $H_2$ in TWA 7.

4. Discussion

The $H_2$ progressions ratios from TWA 7 (Figure 7) more closely resemble that from CTTS than that from M stars. However, these ratios do not guarantee that the $H_2$ is circumstellar. TWA 7 is much closer in age to the CTTS and is thus likely to have higher chromospheric activity than an average M star. Chromospheric activity produces Ly$\alpha$ emission, which can then excite the $H_2$ in starspots on mid-M-type stars. We suggest this is not the primary source of $H_2$ emission in TWA 7 because chromospheric activity affects the core of the Ly$\alpha$ profile significantly more than the wings (Lemaire et al. 2015). So while there is some Ly$\alpha$ emission in the wings from all of these stars, the amount of flux induced solely from chromospheric activity is likely not enough to excite the outer $H_2$ progressions. Youngblood et al. (2021) looked at how Ly$\alpha$ varied with stellar parameters, showing how increased Ly$\alpha$ is correlated with higher chromospheric activity and lower gravity, both of which are correlated with youth. However, the profiles from Youngblood et al. (2021) show that the ratio of the flux between the peak and the wings can remain constant with varying chromospheric activity and gravity, even if the overall flux changes. Thus the most likely explanation is that TWA 7 is still weakly accreting circumstellar gas from an inner disk.

Accretion rates for weakly accreting stars are notoriously hard to measure accurately. There are cases, such as MY Lup, that have FUV accretion signatures but lack optical ones (Alcalá et al. 2019). Previously, TWA 7 was considered a standard, non-accreting WTTS. It shows no accretion signatures in the optical. The hot FUV lines seen in TWA 7’s HST–COS spectrum, such as C IV or N V, have profiles that do not look like those of CTTS (Ardila et al. 2013). TWA 7 also lacks the NUV flux and Ca II $\lambda$3933 emission of known accreting stars (Ingleby et al. 2011b, 2013). However, most of the accreting gas is expected to be hydrogen in the ground state. Muzerolle et al. (2000) found that Ly$\alpha$ should be more sensitive to small accretion rates than any other line. There is a similar system in TWA, TWA 4 B, a K5 star with circumstellar $H_2$ FUV emission discovered by Yang et al. (2012) despite not showing obvious accretion signatures. Given that TWA 7 is close in age to the typical protoplanetary disk is predicted to evolve into a debris disk, these systems could represent a short-lived phase of disk evolution with residual gas that does not accrete at the high levels detectable in optical spectra. FUV spectra of more stars in TWA would allow us to further investigate the gas evolution at this crucial age.

Assuming the $H_2$ we observe is indeed circumstellar, the next question concerns its origin. One possibility is that the $H_2$ originates from the inward migration, sublimation, and subsequent photodissociation of $H_2O$ ices in comet-like nuclei. The $H_2O$ photodissociates into $H$, OH, and O, and the newly available $H$ atoms can then reform into $H_2$. If true, there should also be some oxygen gas species in the inner disk. Riviere-
Marichalar et al. (2013) give an upper limit on the oxygen mass of $2.3 \times 10^{-5} M_{\odot}$ from Herschel data. This upper limit is more than the oxygen that would accompany the $H_2$ we detect if the $H_2$ originates from dissociated $H_2O$ and assuming the warm $H_2$ is confined to the inner few au of the disk, making this a potentially viable source of the observed $H_2$. Future observations could better constrain the oxygen mass in the inner disk and allow us to determine whether $H_2O$ ice evaporation is a possible origin of the circumstellar $H_2$ around TWA 7. Additionally, detection of dust from these comets could lend support to this theory (Pearce et al. 2020).

Another possibility is that the $H_2$ we see is residual protoplanetary disk gas. Regardless of its origin, an $H_2$ formation pathway is needed to balance ongoing UV photodestruction of $H_2$. Molecular hydrogen forms most efficiently on grain surfaces, as in the ISM, but it can also form via gas-phase reactions (e.g., through $H + H^- \rightarrow H_2 + e^-$) when there is less dust surface area available (Bruderer 2013).

To explore the possibility of grain surface formation of $H_2$ in the case of TWA 7, we can estimate the upper limit on the surface area of warm grains by looking at its spectral energy distribution (SED). Although the W3 band from the Wide-field Infrared Survey Explorer (Wright et al. 2010) shows no excess IR emission from dust (Olofsson et al. 2018; Bayo et al. 2019), we can put a limit on the amount of warm dust by assuming the dust can generate the equivalent of the $1\sigma$ uncertainty for the W3 flux.

Under that assumption, we compute the SED using the model described by Isella & Natta (2005) to put an upper limit of $\lesssim 5.1 \times 10^{-8} M_{\odot}$ on the amount of warm ($\sim 1000$ K) silicate particles between 1 $\mu$m and 1 mm. We chose a lower particle size limit of 1 $\mu$m, because in more evolved systems, particles smaller than that near the star can get blown away by stellar winds. Based on this estimate, grains with radii between 1 $\mu$m and 1 mm could make up a significant surface area, up to $10^{23}$ cm$^2$. If the grains are spread out evenly over the inner 0.3 au, the mass column density is $2 \times 10^{-5}$ g cm$^{-2}$.

With the above constraint on the possible dust content of the inner disk of TWA 7, we can use the results of Bruderer (2013) to estimate the $H_2$ reservoir that can be sustained in the inner disk. In modeling the inner regions of transition disks, Bruderer (2013) considered two physical models: a dusty inner disk and a very dust-poor inner disk with dust column densities of $\Sigma_D = 3 \times 10^{-4}$ g cm$^{-2}$ and $3 \times 10^{-3}$ g cm$^{-2}$, respectively, at 0.3 au. The upper limit on the dust surface density of TWA 7 we find above is an order of magnitude below the surface density of the dusty inner disk model but many orders of magnitude above the surface density of the dust-poor disk model. Thus the dust-poor disk model provides a relatively conservative estimate of the $H_2$ density allowed for TWA 7.

The other relevant parameter in the Bruderer (2013) model is the gas surface density. Figure 6 of Bruderer (2013) shows the results for a case in which the inner disk is very dust-poor and has a gas column density of 0.3 g cm$^{-2}$ at 0.3 au. The $H_2$ fraction in the disk atmosphere is $\sim 3 \times 10^{-6}$ relative to hydrogen or an $H_2$ column density of $N_{H_2} = 3 \times 10^{18}$ g cm$^{-2}$.

Bruderer (2013) does not show the temperature of the $H_2$, although much of it is likely to be warm, as the disk is dust-poor, and dust is a coolant for the gas through gas–grain collisions. If 0.1% of the total $H_2$ column is warm ($\sim 1500$ K), this scenario predicts a warm $H_2$ mass similar to that inferred for TWA 7.

Note that this result is obtained despite using a model with a dust density several orders of magnitude below our dust upper limit. Thus, it seems plausible that even a dust-poor inner disk can sustain a warm $H_2$ column density in the range we estimate for TWA 7 in Section 3.4. While the models from Bruderer (2013) were not tuned specifically to TWA 7’s parameters—the model assumes a hotter 10 $L_\odot$ star and a given abundance of polycyclic aromatic hydrocarbons (PAHs)—these two factors should impact the $H_2$ production in opposite ways: the higher UV flux of the more massive star enhances photodestruction of $H_2$, while the PAH abundance enhances $H_2$ production. We therefore believe it is plausible that the $H_2$ we detect is sustained via some combination of gas-phase reactions in the circumstellar environment of TWA 7. Future observations between 3 and 12 microns with telescopes such as the James Webb Space Telescope could detect PAHs in the disk and lend further support to this possibility (Seok & Li 2017).

Although we do not have the requisite measurements to conclusively determine why there is warm $H_2$ in the circumstellar environment of TWA 7, regardless of its origin, warm gas in a region without detectable warm dust is not unique to this star. Primordial warm $H_2$ is detected inside the inner edge of the dust disk in transitional disk systems (France et al. 2012; Arulanantham et al. 2018). Warm CO has also been detected in these regions (Pontoppidan et al. 2008; Salyk et al. 2011). Clearly, warm gas can outlast detectable amounts of warm dust. Thus, the physics resulting in warm gas in the cavities of transitional disks could also be the cause of the $H_2$ we detect in TWA 7.

5. Conclusions

We have detected molecular hydrogen from four progressions ([1, 4], [1, 7], [0, 1], and [0, 2]) in TWA 7, a known debris disk system. The ratios between CCF peaks of the detected $H_2$ progressions (Figure 7) resemble those from CTTS. This suggests that the $H_2$ in TWA 7 is circumstellar, as it is for CTTS. This is highly unexpected, because $H_2$ is not typically detected in debris disk systems. This star joins a small group of systems that have $H_2$ but are not accreting by typical diagnostic standards. Assuming the $H_2$ is circumstellar, we have estimated a column density of $10^{13}$ to $3.0 \times 10^{17}$ cm$^{-2}$. While we cannot determine the origin of the gas conclusively, it is likely to be generated from residual protoplanetary disk gas.

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Facilities: HST (COS, STIS).
Software: SpecTres (Carnall 2017), NumPy (Oliphant 2006; Van Der Walt et al. 2011), Scikit-learn (Pedregosa et al. 2011), Pandas (pandas development team 2020), Scipy (Virtanen et al. 2020), Matplotlib (Hunter 2007).

Appendix

CCF Ratios

We took the ratio of the CCF maximum of all the non-central progressions to the ratio of the CCF maximum of \([1, 4] + [1, 7]\) for all the stars with previously detected \(H_2\) in our sample. In Figure A1, we plot all of these ratios. TWA 7’s ratios were statistically more similar to that of the CTTS than that of the main-sequence M dwarfs. We describe this analysis in detail in Section 3.3.

\([0, 1]\) and \([0, 2]\) have the most easily detectable flux because of a combination of several factors regarding the pumping transition shown in Table 2: relatively close to the center of \(\text{Ly}\alpha\), high oscillator strengths, and low energy levels for the lower state of the ground pumping transition.
Figure A1. The CCF height ratios of non-central progressions to that of \([1, 4] + [1, 7]\) for our selection of T Tauri stars (open symbols), M stars (filled symbols), and TWA 7. The gray areas are the 1\(\sigma\) regions for a null result if that progression had no flux and just noise. They are greater than zero because we select the maximum of the CCF within 15 km s\(^{-1}\), which would typically be greater than zero even for random noise. TWA 7’s ratios match better with the T Tauri stars, suggesting that its H\(_2\) is also circumstellar.
