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DETECTION OF MOLECULAR HYDROGEN ORBITING A “NAKED” T TAURI STAR

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ABSTRACT

Astronomers have established that for a few million years, newborn stars possess disks of orbiting gas and dust. Such disks, which are likely sites of planet formation, appear to disappear once these stars reach ages of (5–10) × 10^6 yr; yet, $\geq 10^7$ yr is thought necessary for giant planet formation. If disks dissipate in less time than is needed for giant planet formation, such planets may be rare and those known around nearby stars would be anomalies. Here we report the discovery of H_2 gas orbiting a weak-lined T Tauri star heretofore presumed nearly devoid of circumstellar material. We estimate that a significant amount of H_2 persists in the gas phase, but only a tiny fraction of this mass emits in the near-infrared. We propose that this star possesses an evolved disk that has escaped detection thus far because much of the dust has coagulated into planetesimals. This discovery suggests that the theory that disks are largely absent around such stars should be reconsidered. The widespread presence of such disks would indicate that planetesimals can form quickly and giant planet formation can proceed to completion before the gas in circumstellar disks disperses.

Subject headings: circumstellar matter — infrared: stars — solar system: formation — stars: individual (DoAr 21) — stars: pre–main-sequence

1. INTRODUCTION

The thick envelopes of dust and gas that surround young stellar objects evolve into circumstellar disks on a timescale of order 10^6 yr (Strom 1995). The absence of thermal emission from millimeter or smaller sized dust grains, as measured through levels of millimeter and infrared continuum emission much above that expected from a naked star (Beckwith & Sargent 1996; Osterloh & Beckwith 1995; André & Montmerle 1994), as well as the nondetection (Zuckerman, Forveille, & Kastner 1995; Duvert et al. 2000) of molecular line emission from CO toward more evolved, weak-lined T Tauri stars (wTTSs) studied suggests that the disks become dust and gas depleted in only (3–5) × 10^6 yr.

Two different explanations may account for these observations. According to the first, circumstellar material has dissipated through one or more of several processes: photoevaporation, accretion onto the star, tidal dissipation by nearby stars, outflows, or strong stellar winds (Hollenbach, Yorke, & Johnstone 2000). Alternatively, larger objects could have formed through accretion, thereby reducing the total surface area of the dust and burying the molecular component (in the form of ices) inside growing protocometary grains. Consequently, the levels of thermal emission from solids and line emission from molecules would drop below detection thresholds as the effective surface area of solids and number of molecules in the gas phase decrease. Hydrogen, which accounts for greater than 70% of the mass of the disk, would be collected into planetesimals last, assuming that the hydrogen can avoid being removed from the disk until the planetesimals have grown large enough to gravitationally bind gas.

According to the second scenario, hydrogen should remain in the disk until long after the dust becomes undetectable; however, H_2 is difficult to stimulate owing to its lack of a dipole moment and the low temperatures normally found in circumstellar environments. Consequently, the bulk of the disk material is nearly impossible to detect directly, so observers typically resort to emission from dust and abundant trace molecules for insight into the physical conditions within and masses of circumstellar disks. The evidence from these tracers indicate that classical T Tauri stars (cTTSs) are surrounded by substantial disks of gas and dust, while wTTSs—similar, but possibly slightly more evolved objects—are “naked,” essentially diskless. Together, these data suggest that T Tauri stars shed their disks in less than 10^7 yr, too short a time for gas giant planets to form unless the disk is much more massive than a “minimum mass” nebula (Lissauer 1993).

High-resolution spectroscopy of near-infrared rovibrational emission from H_2 offers a means to detect hydrogen directly and, hence, provides a diagnostic of the presence of gas in the near environments of young stars (Weintraub, Kastner, & Bary 2000). High-velocity (shocked) H_2 has been detected in outflows associated with young stars; however, quiescent H_2 associated with orbiting material in circumstellar disks has been almost impossible to identify. Detections of cold H_2 gas apparently about 100 AU from the parent stars were reported recently for three debris-disk stars (Thi et al. 2001a) and from several Herbig Ae/Be stars and cTTSs (Thi et al. 1999, 2001b), based on low signal-to-noise ratio observations made at 17 and 28 μm by the *Infrared Space Observatory* (*ISO*). In much more sensitive observations made from Mauna Kea at 12 and 17 μm, Richter et al. (2002) were unable to confirm the detections of H_2 reported at 17 μm by Thi et al. (2001b) for the three stars observed by both groups (GG Tau, AB Aur, HD 163296). The Richter et al. (2002) results call into question the other *ISO* detections as well. If the *ISO* observations are correct, the detected gas must be outside of 150 AU in extended, nondisk components. Thus, the only undisputed observations reporting the detection of the most abundant gas in circumstellar disks of young stars are both for the cTTS TW Hya (Weintraub et al. 2000; Herczeg et al. 2002), for which the presence of a circumstellar disk was both expected and already established.

In this Letter, we report the detection of emission from molecular hydrogen emission from DoAr 21 (=V2246 Oph), which is classified as a wTTS based on its Hα line equivalent width (-0.6 Å; Bouvier & Appenzeller 1992). Consistent with its being classified as a wTTS, DoAr 21 remains undetected to very low sensitivity thresholds in thermal emission from circumstellar dust (André & Montmerle 1994). The canonical age for wTTSs is 3–10 Myr old, placing stars like DoAr 21 in the planet-building epoch. However, Wilking et al. (2001) suggest that the young stellar object population in ρ Oph has a shorter than average disk survival time and quote an age of 0.4 Myr for the class III sources (wTTSs) they studied. Whether 0.4 or 4 Myr old, as a wTTS, DoAr 21 is presumed to be beyond the disk accretion phase of pre–main-sequence evolution and shows virtually no signs that any circumstellar material is present. The only previous hint of the existence of circumstellar material around this source is an observed polarization amplitude of 5.8% in 9″.7 aperture observations at the I band (Ageorges et al. 1997); however, optical speckle images presented by Ageorges et al. revealed no extended structure around DoAr 21 at 0″.2 spatial resolution and to a sensitivity level of $K \leq 12$.

2. OBSERVATIONS

We obtained high-resolution ($R \simeq 60{,}000$) spectra of DoAr 21, centered near the 2.12 μm rovibrational transition of H_2, on 2000 June 20–23 UT, using the Phoenix spectrometer (Hinkle et al. 1998) on National Optical Astronomy Observatory's 4 m telescope atop Kitt Peak, Arizona. In spectroscopic mode, Phoenix used a 256 × 1024 section of a 512 × 1024 Aladdin InSb detector array. Our observations were made using a 30″ long, 0″.8 (4 pixel) wide slit, resulting in instrumental spatial and velocity resolutions of 0″.11 and 5 km s^{-1}, respectively. Our actual seeing limited spatial resolution was ~1″.4. The spectra were centered at 2.1218 μm, providing spectral coverage from 2.1167 to 2.1257 μm. This spectral region includes three telluric OH lines, at 2.11766, 2.12325, and 2.12497 μm, that provide an absolute wavelength calibration.

The DoAr 21 spectrum was obtained in a 3600 s integration. Telluric calibrations were made from 600 s observations of the A0 V star Vega. Flat-field images were made using a tungsten filament lamp internal to Phoenix. Observations were made by nodding the telescope 14″ along the slit, producing image pairs that were then subtracted to remove the sky background and dark current. The DoAr 21 spectrum was extracted within 0″.7 east-west of the source for a total beam width of 1″.4, beyond which no emission was detected. The spectrum was divided by the continuum and ratioed with that of the telluric calibrator in order to remove telluric absorption features.

The spectrum presented in Figure 1 has been corrected, although incompletely, for telluric absorption features and shifted in velocity to the measured $v_{\rm lsr}$ (3.7 km s^{-1}) of the ρ Oph cloud (Kamazaki et al. 2001). Although no direct measurements exist for the velocity of DoAr 21, all published values of $v_{\rm lsr}$ for sources known to be in the ρ Oph cloud, at a distance of 160 pc, fall within 1 km s^{-1} of the velocity of the cloud, with respect to the local standard of rest. Thus, since DoAr 21 is well established as a member of this cloud, we have made the assumption that the rest velocity of DoAr 21 is indistinguishable from the velocity of the cloud. This spectrum shows a single, spatially unresolved emission line, with an FWHM velocity of 9 km s^{-1}, associated with the $v = 1 \rightarrow 0$ $S(1)$ transition of H_2 at 2.12183 μm, and centered at the rest velocity of DoAr 21. We estimate the intensity of this line emission to be $(1.5 \pm 0.15) \times 10^{-14}$ ergs s^{-1} cm^{-2}.

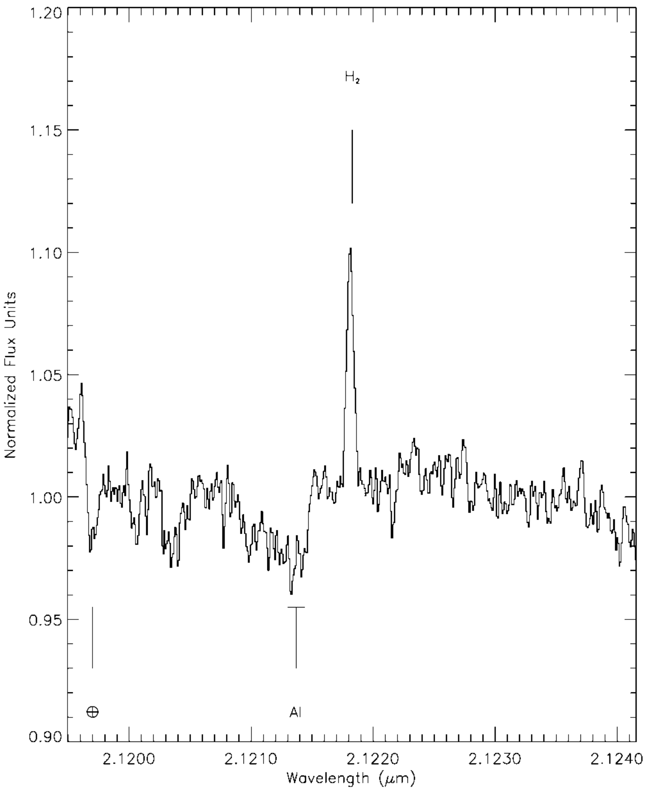

FIG. 1.—Emission from H_2 gas, in the $v = 1 \rightarrow 0$ $S(1)$ transition at 2.12183 μm, from the disk around the wTTS DoAr 21. The absorption feature shortward of 2.1200 μm is an incompletely corrected telluric absorption line, while the absorption feature at 2.12137 μm is tentatively identified as photospheric "Al" (J. S. Bary, D. A. Weintraub, & J. H. Kastner 2002, in preparation) and is labeled as such.

3. DISCUSSION

Emission from cold H_2 is not expected from a supposedly diskless wTTSs such as DoAr 21. Yet, we detected a single emission line in the spectrum of DoAr 21, the central wavelength of which matches the stellar rest-frame wavelength of the 2.12183 μm $v = 1 \rightarrow 0$ $S(1)$ rovibrational transition of H_2 to within errors (± 1 km s^{-1}). We conclude that the observed emission is from gaseous H_2 within ~110 AU of DoAr 21.

Could this gas be shock-excited H_2 in a stellar jet, as often is seen toward young stellar objects? Such gas is expected to have a velocity of 30–50 km s^{-1} relative to the star. The fact that the central line velocity of the H_2 falls within ~1 km s^{-1} of the velocity of the CO in the ρ Oph cloud, and implicitly at the rest velocity of DoAr 21, demands that such a jet be oriented in a highly unlikely geometry, within ~2° of perpendicular to our line of sight. Furthermore, since the detected emission line is spatially unresolved, the jet would have to be contained to within 110 AU of the star and be very tightly confined along the outflow axis, since the conical expansion velocity of an outward rushing jet is likely greater than 10 km s^{-1}. We conclude that, in this case, shock excitation in a stellar jet is an extremely unlikely stimulating mechanism for exciting the H_2 emission.

Could the H_2-emitting gas reside in a tenuous halo, rather than a disk, surrounding the young star? DoAr 21 is seen through more than 6 mag of visual extinction (Bouvier & Appenzeller 1992); thus, it is perhaps conceivable that the H_2 emission from

DoAr 21 could originate in ambient molecular cloud gas that is excited by ultraviolet photons and/or X-rays from the star. The fact that the H_2 line emission is spatially unresolved yet marginally spectrally resolved is inconsistent with this interpretation, as such a UV– or X-ray–excited halo should be many hundreds or thousands of AU in extent and would exhibit a very narrow line profile. We believe that it is very unlikely that some kind of excitation of a quiescent interstellar gas cloud would produce broadened, yet spatially unresolved H_2 line emission. Furthermore, we have failed to detect H_2 emission around other ρ Oph and Taurus cloud stars that display similarly large values of A_V and large UV and X-ray fluxes (J. S. Bary, D. A. Weintraub, & J. H. Kastner 2002, in preparation). We therefore conclude that the H_2 emission from DoAr 21 arises in a circumstellar disk and from within 110 AU of the star.

The cTTS LkCa 15 shows a double-peaked velocity profile for the H_2 line at 2.12183 μm, with a peak-to-peak separation of 10 ± 1.5 km s^{-1} (Bary, Weintraub, & Kastner 2001; J. S. Bary, D. A. Weintraub, & J. H. Kastner 2002, in preparation). This double-peaked profile is just that which is expected for H_2 emission orbiting LkCa 15 in a disk seen at an inclination angle of $34° \pm 10°$ (for which the inclination angle has been determined through interferometric, millimeter wavelength observations of CO emission; Duvert et al. 2000). Given the kinematic information from the emission line and the inclination angle, we determine the bulk of the emission to be at a distance of 10–30 AU from the star, in Keplerian motion. Since the line widths, strengths, and velocities relative to their stars are all very similar for LkCa 15 and DoAr 21, the physical mechanism for producing the H_2 emission also is likely very similar in both cases. We therefore infer that the bulk of the H_2 gas producing the emission observed toward DoAr 21, which we have already constrained to be within 110 AU of the star, probably is located at distances of 10–30 AU from the star. Although the double-peaked velocity profile is not observed for DoAr 21, the absence of a detectable double-peaked velocity profile is probably due to the fact that this disk is viewed at a steeper inclination angle ($i > 55°$), such that the double-peaked distribution is below the velocity resolution of our data and because the gas does not reside within a few AU of the star, since the absolute velocities would be quite high at small orbital distances.

What is the mechanism for producing the observed H_2 line emission within this disk? Ultraviolet fluorescence and X-ray radiation are both capable of stimulating H_2 emission since UV pumping and X-ray ionization (Tine et al. 1997; Maloney, Hollenbach, & Tielens 1996; Gredel & Dalgarno 1995) serve to enhance the population of the first excited vibrational state of H_2 under the right conditions. In general, T Tauri stars are good sources of UV (Valenti, Johns-Krull, & Linsky 2000) and X-ray photons (Feigelson & Montmerle 1999).

DoAr 21 is one of the most X-ray luminous T Tauri stars known (Casanova et al. 1995). DoAr 21 also has significant emission in the UV (Bouvier & Appenzeller 1992; Herbig & Bell 1988; Safier 1995) above that expected from thermal emission from the photosphere of the star, with a UV excess of -1.4 mag. For the last decade, both excess UV emission and strong X-ray emission (Feigelson & Montmerle 1999) have been thought of as indicators of coronal activity for T Tauri stars; on the other hand, more recent work suggests they may be signposts of accretion from a circumstellar disk onto the star (Johns-Krull, Valenti, & Linsky 2000; Kastner et al. 2002). Kastner et al. (2002) model the *Chandra* X-ray spectrum of TW Hya and show that the temperature characterizing the bulk of the plasma producing the X-rays from this star is at a temperature of $\sim 3 \times 10^6$ K and that the electron densities are greater than 10^{12} cm^{-3}. This high temperature and high density, they argue, are consistent with adiabatic shocks produced by gas infalling onto less than 5% of the surface of the star at free-fall velocities of a few hundred kilometers per second. Johns-Krull et al. (2000) compared the level of "transition region" line emission from T Tauri stars with main-sequence, RS CVn magnetic "standard" stars, and wTTSs and showed that cTTSs appear to have an anomalous line emission strength, with accretion shocks being the most likely explanation for the excess line strength. Noting that DoAr 21 is a strong source of X-rays and UV photons that can be produced through either accretion processes or coronal activity (with coronal activity having previously been assumed to be the production mechanism for wTTSs because of their supposed absence of accreting material) and having demonstrated from our spectra the likelihood that a significant amount of gas still orbits the wTTS DoAr 21, we suggest that DoAr 21 may be actively accreting material from its disk. This suggestion, while contrary to the present paradigm that wTTSs are not accretionally active, is consistent with our detection of UV– or X-ray–excited H_2 gas in a disk orbiting a wTTS, which is likewise contrary to the present paradigm. We note, however, that at $kT \sim 3$ keV, as suggested by Imanishi, Tsujimoto, & Koyama (2002), the X-ray emission from DoAr 21 may be too hard to be explained by accretion.

For X-ray–stimulated excitation, the optical depth for X-rays, determined using cross sections from Yan, Sadeghpour, & Dalgarno (1998) and a disk density profile found in Glassgold, Feigelson, & Montmerle (2000), is such that the X-rays must travel through a significant column of gas ($N \geq 10^{21}$ cm^{-2}) before depositing their energy. Given the gas densities likely in an inner disk, we find that X-rays produced in the near environment of DoAr 21 could penetrate a few tens of AU into the disk. Any gas excited by X-ray absorption followed by collisional excitation in the high-density, inner disk will quickly become collisionally deexcited. This precludes the X-ray excitation mechanism from working well in the inner disk; however, this mechanism may plausibly work at a few tens of AU, especially in lower density regions at the upper and lower surfaces of the disk, where the density is below 10^7 cm^{-3}. A similar argument holds for UV-excited gas; UV photons cannot penetrate out to tens of AU in the self-shielding midplane, but they could excite a small volume of gas in more tenuous regions above the midplane out at 10–30 AU. UV excitation would work in the inner disk; however, we should then see a wider H_2 line width due to the higher Keplerian velocities of gas within a few AU of the star. We cannot definitively determine which excitation mechanism, X-ray ionization or UV fluorescence, is of primary importance since both appear to be plausible candidate mechanisms for producing the observed emission at distances of a few tens of AU from the star.

For infrared H_2 emission, it is straightforward to estimate the mass of H_2 responsible for the detected emission line (see, e.g., Thi et al. 2001a); however, the mass we calculate ($4.4 \times 10^{-10}\ M_\odot$) will be only a small fraction of the total mass of hydrogen and therefore of the disk. Any estimate of the total disk mass depends on a determination of this fraction. Our task, then, is to quantify the ratio of the tracer to the total mass. To do this, we compared the total disk masses as measured in millimeter CO line emission and submillimeter thermal emission for the cTTSs GG Tau, LkCa 15, and TW Hya with the masses we estimate from quiescent, near-infrared line emission of H_2.

The amount of H_2 gas as determined directly from the line emission at 2.12183 μm, and making no assumptions about the gas temperature, for GG Tau and TW Hya is about 10^{-7} to 10^{-9} of the total mass (Bary et al. 2001) based on estimates from CO line emission and millimeter and submillimeter continuum emission. The amount of H_2 gas for LkCa 15 is about 10^{-8} to 10^{-10} of the total mass based on millimeter and submillimeter continuum emission. Clearly, mass estimates made using the line intensity in the $v = 1 \rightarrow 0$ $S(1)$ line greatly underestimate the true masses in the disks in these three cases, thus establishing that the warm H_2 gas can act as a tracer of much more massive disks. Using the ratio of the H_2 line–based mass to the tracer mass for GG Tau, TW Hya, and LkCa 15 and the H_2 line–based mass of 10^{-10} $M_\odot$ for DoAr 21, we can infer a total disk mass range of 10^{-3} to 1 $M_\odot$ for DoAr 21, assuming the 2.12183 μm H_2 line acts as a tracer of a more massive disk.

Near-infrared and longer wavelength broadband photometry of young stellar objects previously have been used as methods for identifying protostellar sources that are likely candidates for harboring circumstellar disks, as any emission from such stars above that expected from the nearly isothermal photosphere must emerge from small dust grains in the near-star environment. However, DoAr 21 shows no evidence of excess near-infrared thermal emission (Wilking et al. 2001), has at best a marginal mid-infrared excess (Wilking et al. 2001; Bontemps et al. 2001), and has not been detected in very sensitive 1.3 mm continuum observations (André & Montmerle 1994; the upper limit for the 1.3 mm flux density of 4 mJy implies the presence of less than about 10^{-6} $M_\odot$ of dust and 10^{-4} $M_\odot$ of gas). Thus, small dust grains are not present in sufficient quantities to be detectable and, prior to this work, all the available evidence suggested that DoAr 21 had no circumstellar disk.

Our detection of a persistent gaseous disk around DoAr 21 is consistent with recent findings (Stassun et al. 1999; Rebull 2001) suggesting that wTTSs may not spin faster than cTTSs (but see also Herbst et al. 2000; Herbst, Bailer-Jones, & Mundt 2001). Hence, the discrepancy, if any exists, in X-ray production between cTTSs and wTTSs (Feigelson et al. 2002) may not be attributable to their spin rates. The continued presence of a disk is a logical, although not the only (Hartmann 2002), explanation for the lack of two distinct distributions of rotation periods for cTTSs and wTTSs, since magnetic decoupling of the star from the disappearing disk, followed by contraction and spin-up of the star, originally was believed responsible for the now contested bimodal distribution for T Tauri star rotational velocities.

The detection of excited H_2 from the near-star environment of DoAr 21 is the first of its kind. Most likely, we have detected only the small annular portion in the upper layers of a gaseous disk around DoAr 21 that is sensitive to excitation by X-ray or UV photons. Thus, the 2.12183 μm emission line of H_2 likely is tracing the existence of a much larger, more massive disk, but also one in which significant planet building already may have occurred.

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