Substantial reservoirs of molecular gas in the debris disks around young stars

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As the means by which matter is transferred from molecular clouds to young stars and the birth sites of planets, circumstellar accretion disks are the pivotal link between star formation and (exo)planetary science. The disks around pre-main sequence stars have properties consistent with those expected for the presolar nebula from which our own planetary system was born 4.5 Gyr ago[1]. Substantially less massive 'debris' disks are found to encircle $\gtrsim$15% of the nearby main sequence stars[2,3,4,5], for which CO observations[6,7,8] suggest gas/dust ratios $\ll$0.1. Here we report observations of the lowest rotational transitions of the main constituent, H_2, that reveal up to ten Jupiter masses of gas in the debris disks around β Pictoris, 49 Ceti, and HD135344. The gas/dust ratios are factors of several hundreds to a thousand times larger than those derived from CO, and suggest that these are in fact young descendants of circumstellar disks formed in a recent episode of local star formation[9].

We utilized the Short Wavelength Spectrometer[10] (SWS) aboard the Infrared Space Observatory[11] (ISO), which provided the first opportunity to conduct measurements of the H_2 J=2$\rightarrow$0 S(0) 28 μm and J=3$\rightarrow$1 S(1) 17 μm pure rotational transitions above the Earth's atmosphere. These lines are the lowest energy transitions of the H_2 molecule, but are difficult (17 μm) to impossible (28 μm) to observe from the ground due to telluric absorption. A number of classical T Tauri stars, Herbig Ae stars, and young (pre-)main sequence stars with confirmed circumstellar disks were observed. The results of the searches toward T Tauri and Herbig Ae stars may be found elsewhere[12,13]. Here we focus on three sources previously classified as 'Vega-type' objects; that is, low mass disks with a dust population that is presumed to be dominated by second generation grains[3].

High sensitivity mid-infrared observations of H_2 such as those made possible by ISO have a number of advantages over more commonly used indirect tracers for assessing the molecular gas content of debris disks. For a gas of solar composition, molecular hydrogen is

the overwhelmingly most abundant gaseous species (by four orders of magnitude), obviating the uncertainties associated with the conversion factors needed for other molecules.

Due to its homonuclear nature, the intrinsic pure rotational transition strengths are sufficiently small that the optical depths of the mid-infrared lines are low, greatly simplifying the radiative transfer analysis. Because the lines appear in emission and are optically thin, any disk orientation can be studied. Substantially higher temperatures are required for excitation of the H_2 vibration-rotation manifold near 2 μm, while special geometries are needed to conduct either near-infrared or vacuum ultraviolet (electronic) absorption line measurements. Thus, observations of the H_2 mid-infrared lines are the most direct means to directly probe the bulk of the warm molecular gas in the inner $\sim$100 AU of disks.

The observed intensities of the H_2 lines are close to the ISO sensitivity limit, as Figure 1 shows, and so required the development of special software to supplement the standard SWS Interactive Analysis Package. A detailed description of the software used to improve the SWS dynamic range can be found elsewhere[12,14] (see Fig. 1 legend for details of the observing procedure). Table 1 presents the integrated line fluxes observed toward β Pictoris, 49 Ceti, and HD135344. The S(1)/S(0) ratios yield a direct measure of the excitation temperature provided the gas densities are large enough that collisional rates exceed ultraviolet pumping and spontaneous emission from the J=2 and 3 levels ($n_{cr} \gtrsim 10^4$ cm^{-3}). For both the debris disks reported here and the disks surrounding T Tauri and Herbig Ae stars[12], temperatures near 100 K are found – values comparable to the dust temperatures derived from fits of debris disk spectral energy distributions[15]. The non-detection of the J=4$\rightarrow$2 S(2) and J=5$\rightarrow$3 S(3) lines at 12.278 and 9.662 μm limits the gas temperature to $<$250 K.

The total gas mass is very sensitive to temperature since the transition upper states lie at 510 and 1015 K above ground, respectively, but, as outlined in Table 1, is straightforward to derive assuming thermal equilibrium given the distance to the source. Values range from a minimum of 0.17 M_J (Jupiter mass) for β Pictoris to just over 6.6 M_J for HD135344. Only an upper limit to the S(1) flux is available for 49 Ceti, which constrains the temperature to

be less than ∼100 K, corresponding to gas masses of at least 0.35 M_J. The uncertainties in the inferred masses are estimated to be a factor of three, and stem mainly from the weakness of the lines and the unknown ortho/para ratio in such disks.

The line shapes are unresolved at the velocity resolution available to ISO, and 49 Ceti and HD135344 are too far away for their disks to be resolved with the large beams sampled by the SWS. Although β Pictoris is extended in the ISO-SWS beam, only observations centered on the star have been performed. As a result, no spatial information is available for the gas, and the fluxes obtained thus yield only lower limits for the gas mass.

Table 1 also lists the minimum dust masses derived from ISO measurements of the 60-240 μm continuum fluxes by assuming the emitting particles are small compared to the observing wavelength[15] along with the gas mass estimated by CO observations. As can be seen, the gas mass exceeds that inferred for dust grains by approximately the interstellar gas-to-dust ratio[19] of 100, but the total mass is below that of the so-called minimum solar nebula required to generate our own planetary system, ∼10 M_J. The H_2 gas provides a reservoir from which gaseous giant planets may form, but, except for HD135344, the gas masses are insufficient to form any new Jupiter-mass planets in these optically thin disks. Indeed, provided the ages of these systems can be well constrained, such molecular hydrogen observations provide direct upper bounds for the formation time scales of Jovian planets.

The presence of H_2 but absence of CO can be understood from models of the photo-destruction of these molecules in disks[16]. The ultraviolet radiation from the star and from the ambient interstellar radiation field can destroy CO in tenuous disks and in the outer layers of more massive disks, whereas freeze-out of the molecule onto the surfaces of grains[20] occurs in the cold inner part of massive disks. In contrast, H_2 is not significantly removed by photolysis until the disk mass falls below 10^{-3} M_J, and it does not freeze out onto grains. Millimeter-wave studies of both 49 Ceti and HD135344 have detected weak CO rotational line emission[7,12] consistent with gas gravitationally bound to the star, but the inferred molecular gas abundances are factors of 100-1000 lower than found here. This has

led to the perception that these and other[6] "debris" disks are largely *free* of gas, but our H_2 observations indicate that this is not the case. The mechanisms through which the original massive disks were dissipated remain uncertain. Presumably, this involves a combination of accretion of matter inward onto the star and removal through interaction with a stellar wind and photoevaporation, if the ultraviolet radiation from the star is sufficiently powerful[21].

It has been postulated that various transitory optical features observed toward β Pictoris result from the evaporation of infalling planetesimals[22,23], induced by dynamically important companions. It is difficult, however, to envision the required H_2 mass being generated by secondary processes after disk dissipation. Furthermore, the high gas/dust ratios can significantly alter the dust transport dynamics. For disks with a negative radial pressure gradient, gas surface densities some 100-1000 times lower than those originally present enlarge the grain size for which rapid outward drift occurs to diameters of $\lesssim$100 μm due to the non-Keplerian velocity field of the gas and the corotation of the gas and dust[24]. Larger particles drift inward. If the gas mass is sufficiently large, dust generation by collisional cascade can be shut off completely even in optically thin disks[25].

For β Pictoris, the low gas mass actually enhances the need for the *in situ* generation of 1-100 μm dust grains[26] since such particles can be efficiently ejected from the system; the gas/dust ratio of $\sim$100 found for β Pictoris may thus be coincidental in that substantial amounts of dust and gas may be hidden in large bodies. The gas masses derived for HD135344 and, perhaps, 49 Ceti, can prevent a collisional cascade of dust generation, yet increase the importance of radiative dust ejection provided the disks are optically thin. As such, they may be better interpreted as tenuous remnants of substantially more massive accretion disks. If so, they could be extremely interesting transition objects in which Jovian planet formation may no longer be possible but for which the residual gas provides the opportunity to image gravitational perturbations in the disks due to existing planets formed at earlier stages.

Central to this argument are the likely ages of the star/disk systems. For early-type field stars, the isochrones that are used to estimate ages based on stellar properties such as

luminosity and effective temperature are consistent with two solutions. Vega, for example, can be interpreted as either a few Myr-old pre-main sequence object or a post-zero age main sequence star whose age is $\gtrsim$300 Myr. In most debris disk studies, it is this older age that has been assumed[4,5]. This leads to the natural conclusion that the dust must be regenerated *in situ* since radiation pressure and Poynting-Robertson drag forces provoke the loss of $\lesssim \mu$m-sized grains within only 0.1–1 Myr in gas-free disks, and to the secondary conclusion that dust disks are the most observable features of planetary systems like our own.

The age of β Pictoris has recently been estimated to be 20 $\pm$ 10 Myr using nearby M dwarfs argued to be part of the same loose cluster based on proper motion studies and *Hipparcos* distances[18]. Ages for 49 Ceti and HD135344 derived by recent pre-main sequence stellar evolution models[17] are 8 and 17 Myrs, respectively, as shown in Table 1. In addition, HD135344 possesses certain features reminiscent of young Herbig Ae stars[27].

Older stellar ages are consistent with the prevailing view that the probability of stars with ages of less than 10–30 Myrs lying with a few tens of pc to the Sun is unlikely. The discovery of four nearby ($d < 50 - 60$ pc) young associations suggests, however, that local star formation was ongoing as recently 10–50 Myr ago, and that the Sun now lies within this stream of young stars[9]. For example, the G2 star/disk system HD207129 lies at a similar distance as does β Pictoris, and has alternatively been assumed to be either 4.7 Gyr old[28] or only a few 10's of millions of years in age[9]. Indeed, the sensitivity limitations of the IRAS all sky survey that is the basis for most debris disk searches and the ISO instruments used for follow up ensured that only nearby or fairly massive disks have been located to date[3,29]. Searches for H_2 such as that performed here can help to establish the gas/dust mass and evolutionary state of the sources, but only a small number of objects have been surveyed so far with adequate sensitivity. Our current understanding of remnant and debris disks may therefore be biased by the local star formation history and instrumental sensitivity. The present results suggest that Jovian planet formation can occur on time scales up to 20 Myr, but we stress the limited nature of the present sample. More massive disks easily capable of

Jovian planet formation are seen around several T Tauri and Herbig Ae stars of only slightly younger ages, for example, and illustrate the pressing need for better statistics[12].

The Space Infrared Telescope Facility (SIRTF) to be launched by NASA in 2002 will go much deeper than IRAS and ISO, and will provide hundreds of new targets for further study. Improved molecular line observations will also become possible with the high resolution mid-infrared spectrometers nearing completion for use on large ground based telescopes (for the 17 μm S(1) line) and airborne observatories (for the 28 μm S(0) transition). These diffraction-limited spectrometers will possess both the spatial and spectral resolution required to examine whether the gas and dust are co-spatial in the disks, and can establish whether the gas persists to within a few AU of the central star without the use of coronographic techniques. In the longer term, a mid-infrared spectrometer on the Next Generation Space Telescope (NGST) would make possible the detection of Earth-masses of H_2 gas at temperatures down to 50 K. By combining continuum and line studies of disks around stars up to several tens of Myrs in age, it will be possible to determine both gas/dust dissipation and Jovian planet formation time scales; and to examine the role of collisional, radiative, and gaseous processes in shaping the evolution and survival of dust clouds in planetary systems.

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Table 1 – ISO H_2 observations of debris disks

Source	d (pc)	Age (Myr)	H_2 S(0)	H_2 S(1)	T_{ex} (K)	H_2 mass (M_J)	Dust mass (10^{-2} M_J)	M_{H_2} via CO (M_J)
β Pic	19.3	20±10	7.0	7.7	109	0.17	0.3	$<6 \times 10^{-5}$
49 Ceti	61	8±4	6.6	<3.0	<100	>0.35	0.63	0.006
HD135344	80	17±3	9.0	5.5	97	6.6	8.5	0.005

The integrated molecular hydrogen rotational line intensities, gas masses, and dust masses toward the β Pictoris, 49 Ceti, and HD135344 debris disks. The integrated intensities of the H_2 J = 2 → 0 [S(0)] and J = 3 → 1 [S(1)] lines at 28.218 and 17.035 μm are presented in units of 10^{-14} ergs s^{-1} cm^{-2}. Masses are derived using local thermodynamic equilibrium (LTE) from the expression

$$M_{\rm H_2} = 1.76\ 10^{-17}\ \frac{F_{ul}\ d^2}{(hc/4\pi\lambda)\ A_{ul} x_u} \qquad {\rm M_J} \tag{1}$$

where d is the distance in parsec, F_{ul} is the flux of either the S(0) or S(1) H_2 transition, h is Planck's constant, c is the speed of light, λ the observing wavelength, and A_{ul} and x_u are the Einstein spontaneous emission coefficient and upper state population for the line in question. The upper state population x_u is very sensitive to the excitation temperature, which is fitted from the S(1)/S(0) ratio assuming that the ortho/para ratio is in LTE at the excitation temperature (o/p=1.6 for T = 100 K). Numerically, $T_{ex} = 505.24/[\ln(112.51 \times S(0)/S(1)]$ K. Since only upper limits are available for the S(1) flux from 49 Ceti, the H_2 mass is calculated for the upper temperature limit of 100 K, resulting in a lower bound for the mass. Dust masses are from the ISO measurements of Walker & Heinrichsen[15]. The H_2 mass for β Pictoris refers to the inner 400 AU, which contains at least 80% of the disk mass[16]. The age estimates for 49 Ceti and HD135344 are derived using the pre-main sequence stellar evolution tracks of Siess, Forestini, & Bertout[17], that for β Pictoris is taken from Barrado y Navascués *et al.*[18]. The main sequence upper limit to the age of β Pictoris is approximately 100 Myr, those for 49 Ceti and HD135344 are even younger.

Figure 1. Spectra of the lowest pure rotational molecular hydrogen transitions toward the β Pictoris, 49 Ceti, and HD135344 debris disks taken with the Infrared Space Observatory. The SWS mode 2 was used[10], with an aperture of $20'' \times 27''$ at the S(0) line and $14'' \times 27''$ at the S(1) transition, corresponding to 400 AU×540 AU and 280 AU×540 AU, respectively, at the distance of β Pictoris (1 AU = Sun-Earth distance = 1.5×10^{13} cm). The dashed vertical line depicts the rest wavelengths of the H_2 transitions, while the solid curve illustrates the range of potential wavelength shifts induced by grating repositioning errors or pointing offsets of the spacecraft. All line shapes are consistent with the instrumental spectral resolution of $\lambda/\Delta\lambda \sim 2000/2400$ at 28.218/17.035 μm. Typical integration times were 600-1000 s per line, in which the 12 SWS detectors were scanned several times over the 28.05-28.40 and 16.96-17.11 μm intervals around the H_2 lines. Individual scans are examined for cosmic ray glitches, dark current drifts, and readout non-linearities before being summed to produce a final spectrum[12,14]. Off source integrations toward 49 Ceti and HD135344 reveal no H_2 S(1) emission to a limiting flux of 8×10^{-15} ergs s^{-1} cm^{-2} rms.

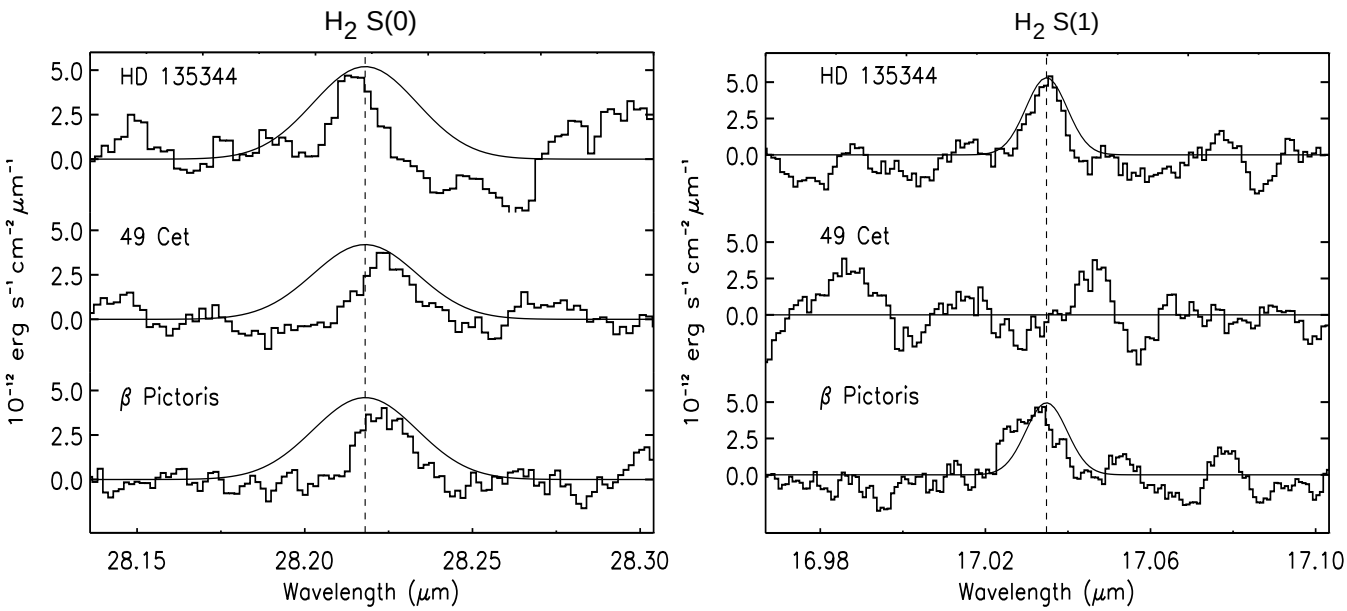

Fig. 1, Thi et al.