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The Dust and Gas Content of a Disk around the Young Star HR 4796A

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We have used the James Clerk Maxwell Telescope in Hawaii to search at submillimeter wavelengths for continuum emission from dust, and spectral line emission from carbon monoxide (CO) gas, in the neighborhood of HR 4796A. This young star has a dusty disk with a central cavity, where planets may have formed. We detect the dust component at a wavelength of 850 μm, and the inferred mass of solid material is $\geq$0.25 $M_\oplus$. An upper limit for the CO $J = 3$–2 rotational line implies less than 1–7 $M_\oplus$ ($\leq$0.003–0.02 Jupiter masses) of molecular H_2 gas in the system. Thus, it is no longer possible to form new Jupiter-like gaseous giant planets around HR 4796A. If planet formation explains the observed dust cavity and lack of gas, then it must have occurred before the current stellar age of ~10 Myr.

A search was also made for CO $J = 3$–2 emission around four other stars with dust excesses revealed by infrared measurements with the Infrared Astronomical Satellite (IRAS). Two were detected, both of them young sources with optical emission lines indicative of ongoing accretion of disk material onto the star. The gas mass lower limits are approximately 30 and 200 Earth masses, at least an order of magnitude higher than that for HR 4796A, illustrating the diversity of disk properties at ages of up to 10 Myr.

Key Words: **planets; formation; extraterrestrial planets.**

INTRODUCTION

HR 4796 is a binary star at a distance $d = 67$ pc. The primary, HR 4796A, has a spectral type of A0. The secondary is an M2.5 star, and the projected separation of the two components is currently 515 AU (Jura *et al.* 1995.) We consider here excess emission (above the photospheric level) from material orbiting around the primary. With an age $t = 8 \pm 2$ Myr (Stauffer *et al.* 1995), the environment of HR 4796A is roughly midway in an evolutionary sense between the massive preplanetary disks of gas and dust orbiting young ($t \sim 1$ Myr) pre-main-sequence stars (Beckwith and Sargent 1993, Mannings and Sargent 1997) and the low-mass secondary debris disks surrounding main-sequence stars ($t \sim 100$ Myr) such as β Pic, α PsA, α Lyr, and ϵ Eri (Lagrange *et al.* 2000, Backman and Paresce 1993, Greaves *et al.* 1998, Holland *et al.* 1998, Mannings and Barlow 1998). The latter disks are thought to be composed of debris products generated in collisions and disruptions of asteroid-sized bodies formed earlier on during the massive disk phase. HR 4796A appears to be at the stage where a formerly massive primary disk has evolved into planetesimals and (perhaps) planets, with a secondary disk of debris grains. It is this secondary disk we detect in submillimeter emission.

OBSERVATIONS

The new data were obtained at the James Clerk Maxwell Telescope (JCMT) between February 1995 and May 1998. The 850-μm continuum emission toward HR 4796A was detected with the new Submillimeter Common-User Bolometer Array (SCUBA) (Holland *et al.* 1999), and the CO $J = 3$–2 spectra (345.796 GHz) were observed with the B3i receiver. Integration times were 1 to 4 h for the spectral lines and 30 min for the dust photometry. The data were taken by chopping the secondary mirror to remove sky emission, and calibrated using standard sources and sky opacity measurements. The CO data have been converted to a main-beam antenna temperature scale.

Thermal emission from grains in the vicinity of HR 4796A was detected at 850 μm, with a flux density of 19.1 ± 3.4 mJy. This corresponds to 0.25 $M_\oplus$ of dust, for a grain temperature of 90 K (cf. models of Jayawardhana *et al.* 1998, Koerner *et al.* 1998) and an opacity of 1.7 cm^2 g^{-1} (cf. Holland *et al.* 1998). This value is likely to be a lower limit to the mass of material encircling HR 4796A as very large grains and planetesimals

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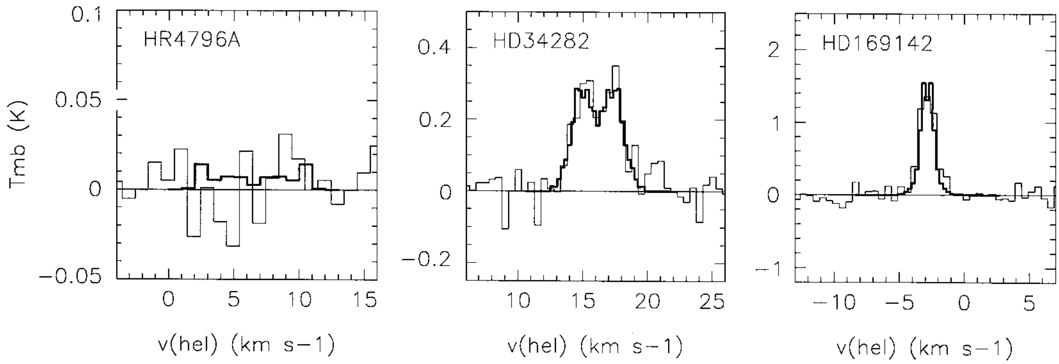

FIG. 1. CO $J = 3$–2 spectra for HR 4796A, HD 34282, and HD 169142, overlaid with model spectra (thin and thick histograms, respectively). For HR 4796A the model is for the maximum-allowed gas mass, constrained by the CO upper limit and the orbital velocities in a 50–125 AU radius disk. The models for the other two stars are for the minimum gas masses, as described in the text.

might dominate the mass while emitting little submillimeter emission. We cannot yet determine grain sizes using the submillimeter spectral index, but better constraints may be possible with a deeper integration: SCUBA data obtained simultaneously at 450 μm wavelength currently indicate a flux density $\sim 180 \pm 150$ mJy. Our mass estimate is comparable to the reported $\sim 1\ M_{\oplus}$ from fits to the mid-IR to submillimeter spectrum (Koerner *et al.* 1998, Jura *et al.* 1998).

We did not detect any CO emission toward HR 4796A after a 4-h integration. The 14″ telescope beam (full-width at half-maximum) was centered on the A0 star HR 4796A and its 3″ diameter dust disk, and included the companion star HR 4796B at approximately the 40% power-point of the beam, for its projected offset of 7.7″. Thus there is no evidence for molecular gas around either star.

Our CO $J = 3$–2 spectrum of the HR 4796 system is shown in Fig. 1. There is no emission at the heliocentric velocity of +6 km s^{-1}, with an upper limit of 9.0 mK rms (main-beam brightness temperature) for an 8 km s^{-1} spectral channel. This is the velocity range for significant emission in a model described below, of an edge-on disk with an inner cavity (Jayawardhana *et al.* 1998, Koerner *et al.* 1998) around a 2-$M_{\odot}$ star.

For comparison, we also searched for CO $J = 3$–2 emission around four stars with significant IRAS excesses attributed to dusty disks (Sylvester *et al.* 1996). HD 34282 and HD 169142 were detected in CO (Fig. 1) with integrated intensities of 1.24 and 2.35 K km s^{-1} respectively, while limits for HD 49662 and HD 144432 were $\sim$0.2 K km s^{-1} over a 5 km s^{-1} interval. These stars are all likely to be pre-main-sequence objects with ages of a few million years (although Oudmaijer *et al.* (1992) suggest a post-main-sequence component in HD 144432). The two detected objects both have IR-millimeter spectral energy distributions (SEDs) reminiscent of those of Lada Class II T Tauri stars surrounded by massive disks (cf. Sylvester *et al.* 1996).

Both of the sources we detected in CO $J = 3$–2 are young stars, as they have optical emission lines. This trend toward CO detections in younger objects agrees with the results of Zuckerman *et al.* (1995); combining the dwarf (V-type) stars in both data sets, CO is detected toward 5 of 7 emission-line sources but only 3 of 8 of the non-emission-line objects. This result supports a short timescale for molecular gas to remain in these systems, before it is incorporated into planets, dispelled by stellar winds, or accreted onto the central stars. The statistics cannot be explained by a selection bias, as the median distance is in fact larger for the emission-line stars, so the signals would be weaker for comparable gas masses and temperatures.

MODEL RESULTS

A simple model has been used to estimate the gas masses in these systems, based on the approach of Yamashita *et al.* (1993). We assume wedge-shaped disks with H_2 number density proportional to radius to the power −2.5, circular Keplerian orbits, and gas excitation in thermal equilibrium with blackbody grain temperatures (Eq. 3 in Backman and Paresce 1993). In the model, molecules are distributed between cells, and local thermodynamic equilibrium calculations (including optical depth for the velocities within each cell) give the contributions to the spectrum. The CO:H_2 abundance is affected by photodissociation from interstellar UV radiation (van Dishoeck and Black 1988) and also by the stellar UV field at the inner edge of the disk. The models of Hollenbach *et al.* (1991) were used for the relation of CO:H_2 to the extinction A_V toward the star (neglecting any density dependence), and standard UV fields were used for the stellar types (A0 for HR 4796A and HD 34282; B9 for HD 169142). We neglected photodissociation of H_2 which is significant only over a narrow A_V range (van Dishoeck and Black 1988), and CO freezing onto grain mantles, which is important only at very large radii where temperatures fall below about 30 K (Sandford and Allamandola 1993).

Figure 1 shows example fits to the spectra, matching both the integrated intensity and the lineshape (with a reduced χ^2 criterion of $\geq$10% fit probabilities). The distance estimates are the major cause of uncertainty for HD 34282 (160^{+60}_{-40} pc, van den Ancker *et al.* 1998) and HD 169142 ($\sim$145 pc, Sylvester *et al.* 1997), as the fits are constrained largely by the beam-filling factors of these optically thick, self-shielded disks. We find minimum disk diameters of a few hundred astronomic units, CO line opacities >7, and minimum gas masses of $\sim$0.1 and 0.7 Jupiter masses, respectively. Massive disks are expected as Sylvester *et al.* (1996) detected high 1.1-mm dust fluxes; this would also be consistent with the Lada Class II stellar identifications.

In contrast, the gas mass for HR 4796A is at least an order of magnitude lower. The adopted disk parameters were outer radius 125 AU, inner radius 30–50 AU, inclination of $\geq 72^\circ$ (where $i = 0^\circ$ is face-on), and an opening angle of 5°–20°, imposed by the thin and nearly edge-on appearance in 20-μm images (Jayawardhana *et al.* 1998, Koerner *et al.* 1998). The CO upper limit then implies a low $M(H_2)$ of $\leq$1.1–7.3 $M_\oplus$, with the range depending largely on the adopted disk thickness, which affects the photodissociation. Unlike the other two disks, the model CO:H_2 abundances are significantly reduced, to $<3 \times 10^{-5}$ compared to interstellar values $\sim 2 \times 10^{-4}$, and the gas is optically thin with τ(CO $J = 3$–2) less than 0.3. For a dust mass of $\geq 0.25\ M_\oplus$, the gas-to-dust ratio must be $\leq$4–29, i.e., depleted by a factor of at least $\sim$3 with respect to molecular clouds (gas-to-dust $\approx$100; e.g., Hildebrand 1983). We cannot constrain the mass of any atomic HI gas, but this should be diffuse (as otherwise grain surface reactions will tend to produce H_2) and unlikely to be associated with condensed planet-forming regions.

DISCUSSION

The dusty disk around HR 4796A has been detected in submillimeter emission, and the mass is consistent with model estimates including 20-μm data (Koerner *et al.* 1998), implying that the grain properties are moderately well understood. Modeling of the CO abundance and line upper limit implies an H_2 gas mass below 7 $M_\oplus$ and consequently gas-to-dust depletion of at least a factor of $\sim$3 relative to molecular cloud material. The remaining molecular gas in the HR 4796 system is much less than is needed to make a Jupiter-like planet—at most, a gas “subgiant” with half of Neptune’s mass could be constructed. Thus, any jovian planet formation should be complete around HR 4796A, even at the young age of 8 ± 2 Myr (Stauffer *et al.* 1995). In contrast, CO was detected around two other stars, both with emission lines and presumably only a few million years old, and the minimum gas masses are at least an order of magnitude higher than that for HR 4796A. Thus there is considerable diversity in the disks around intermediate-mass stars, at ages of up to 10 Myr.

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