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# A DUST RING AROUND $\epsilon$ ERIDANI: ANALOG TO THE YOUNG SOLAR SYSTEM

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## ABSTRACT

Dust emission around the nearby star $\epsilon$ Eridani has been imaged using a new submillimeter camera (the Submillimetre Common-User Bolometer Array at the James Clerk Maxwell Telescope). At an 850 $\mu$m wavelength, a ring of dust is seen peaking at 60 AU from the star and with much lower emission inside 30 AU. The mass of the ring is at least ~0.01 $M_\oplus$ in dust, while an upper limit of 0.4 $M_\oplus$ in molecular gas is imposed by CO observations. The total mass is comparable to the estimated amount of material, 0.04–0.3 $M_\oplus$, in comets orbiting the solar system. The most probable origin of the ring structure is that it is a young analog to the Kuiper Belt in our solar system and that the central region has been partially cleared by the formation of grains into planetesimals. Dust clearing around $\epsilon$ Eri is seen within the radius of Neptune's orbit, and the peak emission at 35–75 AU lies within the estimated Kuiper Belt zone of 30–100 AU radius. $\epsilon$ Eri is a main-sequence star of type K2 V (0.8 $M_\odot$) with an estimated age of 0.5–1.0 Gyr, so this interpretation is consistent with the early history of the solar system where heavy bombardment occurred up to ≈0.6 Gyr. An unexpected discovery is the substructure within the ring, and these asymmetries could be due to perturbations by planets.

*Subject headings:* circumstellar matter — planetary systems — stars: individual ($\epsilon$ Eridani) —

## 1. INTRODUCTION

One of the fundamental questions of astronomy is as follows: how typical is the solar system? If Earth-like planets occur frequently, then life may exist elsewhere in our Galaxy. However, the search for extraterrestrial planetary systems is extremely difficult and is most often approached indirectly. Massive planets introduce changes in the observed velocities of their stars (the Doppler technique), and so far 10 objects with minimum masses up to 10 $M_J$ (the mass of Jupiter) have been detected in this way (Mayor & Queloz 1995; Marcy et al. 1997). Earth-like planets may be observable during stellar transits by ground-based and space-borne coronagraphs, or they may have atmospheric signatures different from the stellar photospheres, effects that could be detectable in the future (Fischer & Pfau 1997).

An alternative is to search for young systems where planets are still forming from circumstellar material. Molecular gas has been detected around a few main-sequence stars, most of which are young objects (Zuckerman, Forveille, & Kastner 1995; Dent et al. 1995). Dust was detected around somewhat older main-sequence stars by *IRAS* (Aumann et al. 1984), including the nearby systems Vega and Fomalhaut. These stars have ages ~$10^8$ yr, which lie at the end of the era when rocky planets are expected to form. Recently, submillimeter-wavelength images of these stars (Holland et al. 1998b) showed that Fomalhaut has a dust ring with a central cavity; thus, accumulation into planetesimals may have occurred. Such cavities have also been seen around $\beta$ Pictoris and HR 4796A, at ages of only ~$10^7$ yr (Smith & Terrile 1984; Jayawardhana et al. 1998; Koerner et al. 1998). Unexpected features are now emerging, including secondary dust spots around Vega and $\beta$ Pic (Holland et al. 1998b), and these have yet to be explained by planet formation theories.

So far, there is little evidence for analogs of the solar system around stars of spectral type similar to the Sun. The Doppler technique is biased toward massive planets close to their stars (current detections range out to 2.5 AU), so it is difficult to find gas giants at the distances of Jupiter and beyond. Submillimeter imaging can reveal much lower orbiting masses of dust, below 1 $M_\oplus$, but this emission is brightest when the dust is heated by luminous stars. Vega, Fomalhaut, and $\beta$ Pic are all luminous A-type stars, with much shorter lifetimes than the Sun, so that any planets would be short-lived. However, some G- and K-type stars detected by *IRAS* are suited to ground-based follow-up; in particular, five objects within 25 pc have significant 60 and 100 $\mu$m excesses (Aumann 1988). Here we present the first image of dust around a low-mass main-sequence star—$\epsilon$ Eridani (HR 1084), a K2V (0.8 $M_\odot$) star located only 3.22 pc from the Sun. *IRAS* partially resolved a warm dusty region (Gillett 1986), which is now shown to be a ring similar in scale to the Kuiper Belt. The age of $\epsilon$ Eri is estimated at ≲1 Gyr (Soderblom & Däppen 1989), so it may represent a young analog to the solar system.

## 2. OBSERVATIONS AND RESULTS

The observations were made with the new Submillimetre Common-User Bolometer Array (SCUBA) (Holland et al. 1998a) at the James Clerk Maxwell Telescope (JCMT) on Mauna Kea, Hawaii. The data were obtained between 1997 August and 1998 February, using the SCUBA "jiggle-map" observing mode (Jenness, Lightfoot, & Holland 1998). Fully sampled maps were generated at 3″ sampling, with an on-source integration time of 12.1 hr. Although SCUBA operates at 450 and 850 $\mu$m simultaneously, this Letter concentrates mainly on the 850 $\mu$m data, since observing conditions were generally poor at 450 $\mu$m. Zenith atmospheric opacities at 850 $\mu$m ranged from 0.12 to 0.35 (only 30% of these data had 450 $\mu$m opacities

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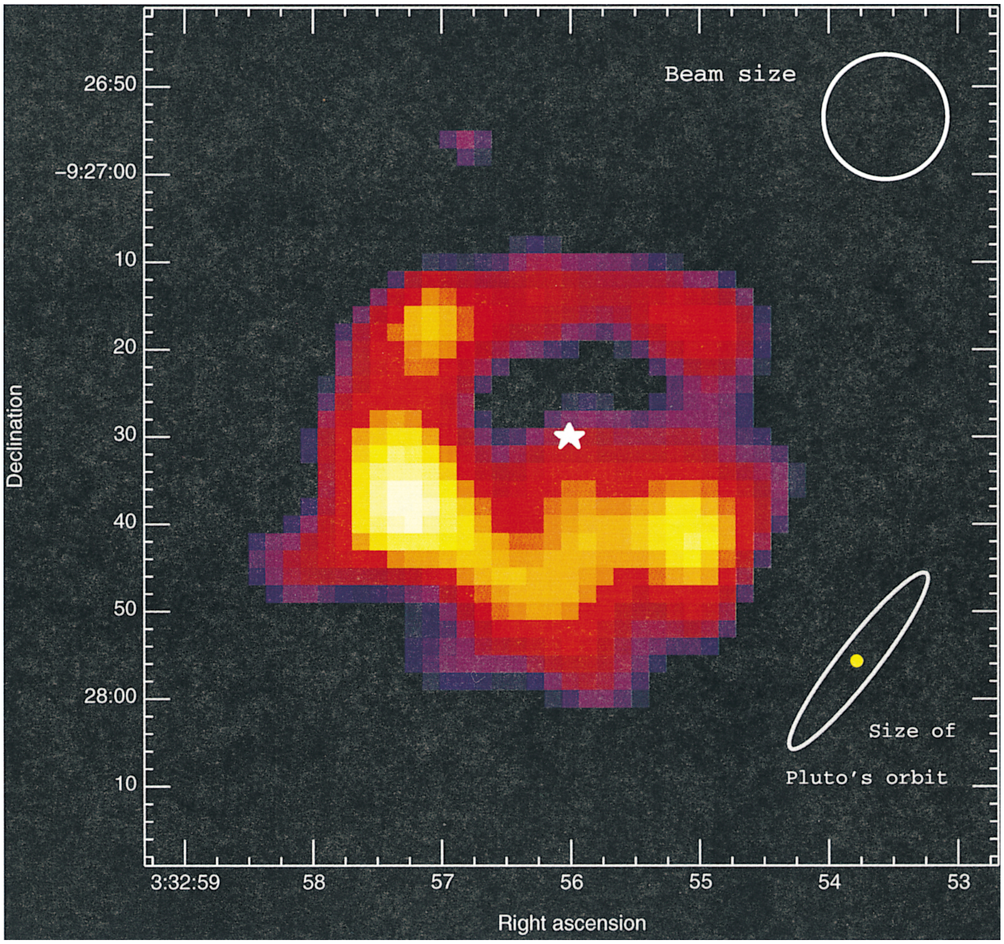


FIG. 1.—Dust emission around $\epsilon$ Eri at a wavelength of 850 $\mu$m. The false-color scale is linear from 2.8 mJy beam$^{-1}$ (3.5 $\sigma$ pixel$^{-1}$) to 8.5 mJy beam$^{-1}$ (at the peak). The star is marked by the star symbol, the circle shows the 15″ beam size, and 1″ corresponds to 3.22 AU. The apparent size of Pluto's orbit at 3.22 pc distance is also shown. The position of the star is R.A. = $03^h32^m56^s.0$, decl. = $-09°27'29''.8$ and is equinox 2000, epoch 1998. The proper motion of the star was only $0''.5$ over the 6 month observing period.

of less than 1), and calibration data were obtained from Mars and Uranus. Pointing accuracy was 2″, which is small compared with the beam size of 15″ at 850 $\mu$m (FWHM). The data were reduced using the SCUBA User Reduction Facility (Jenness & Lightfoot 1998) and are rebinned in a right ascension–declination frame with 2″ cells.

The 850 $\mu$m map of $\epsilon$ Eri is shown in Figure 1. The data have been smoothed with a 8″ point-spread function, resulting in a peak signal-to-noise ratio per beam of 10. Photospheric emission of 1.7 ± 0.2 mJy has also been subtracted in the image. The photospheric flux was estimated by independent extrapolations using 2.2 and 3.4 $\mu$m data (Carter 1990) and the *IRAS* 12 $\mu$m flux (corrected for an effective temperature of 5000 K). Dust emission around $\epsilon$ Eri was also tentatively detected at 450 $\mu$m (Table 1).

The image shows extended flux around the star out to about

TABLE 1

FLUX MEASUREMENTS FOR $\epsilon$ ERI

| Wavelength ($\mu$m) | Dust Flux | Photospheric Flux | Unit | Comments |
|---|---|---|---|---|
| 850 ........ | 40 ± 3 | 1.7 ± 0.2 | mJy | $r \leq 35''$ from star |
| 450 ........ | 185 ± 103 | 6 ± 1 | mJy | $r \leq 35''$ from star |
| 100 ........ | 1.78 | 0.11 | Jy | *IRAS* |
| 60 ......... | 1.34 | 0.29 | Jy | *IRAS* |
| 25 ......... | 0.27 | 1.63 | Jy | *IRAS* |
| 12 ......... | ... | 6.66 | Jy | *IRAS* |
| 3.4 ........ | ... | 70.3 | Jy | SAAO |
| 2.2 ........ | ... | 139.7 | Jy | SAAO |
| 1300 ...... | (>7–24) | 0.7 | mJy | Photometry, 11″–24″ beams |

NOTE.—The flux data were from this work, the *IRAS* point-source catalog, Carter 1990, Zuckerman & Becklin 1993, Chini, Krügel, & Kreysa 1990, and Chini et al. 1991. The photospheric emission at 2.2–12 $\mu$m was extrapolated to find dust excesses (see also Gillett 1986). Only the 12 $\mu$m point was used for the *IRAS* wavelengths, and color corrections were made for a 5000 K photosphere (12–25 $\mu$m) and the dust spectral energy distribution (60–100 $\mu$m).

35″ radius. The rest of the field of view is largely featureless, but one other source is seen approximately 60″ east of $\epsilon$ Eri. This has a total flux of about 8 mJy and could be a distant galaxy (see, e.g., Smail, Ivison, & Blain 1997). Additionally, a 2.2 $\mu$m image obtained with the Keck 10 m telescope shows three more background objects within 50″ of the star, but none of these coincide with the submillimeter peaks. We conclude that background sources are not significantly affecting the brightness distribution seen around $\epsilon$ Eri at 850 $\mu$m.

*IRAS* data at 60 $\mu$m have shown a more compact dusty structure, with a half-power radius of 8″–11″ (Aumann 1991; Gillett 1986), and temperatures ranging from 50 K up to 370 K for some grains near the star. The 850 $\mu$m emission extends to about 35″ from $\epsilon$ Eri, and only ≈9% of it comes from the *IRAS* source area. We also find an 850 $\mu$m/450 $\mu$m flux ratio of 4.6 ± 2.6 (Table 1) corresponding to a dust opacity index $\beta \leq 1.1$. This implies large grains (Pollack et al. 1994) that are efficient emitters and that, at the observed distances from $\epsilon$ Eri, will be at about 30 K (Backman & Paresce 1993). These results are discussed further below, and the fluxes from the millimeter to the infrared are listed in Table 1.

A search was also made for a molecular gas component around $\epsilon$ Eri. Low limits had been set previously by a search for CO $J = 1$–0 emission (Walker & Wolstencroft 1988) using a large telescope beam that included all the Figure 1 emission region. More recently, Dent et al. (1995) found no CO $J =$ 3–2 emission toward $\epsilon$ Eri, but the 14″ JCMT beam was only sensitive to the low-flux region near the star (Fig. 1). We therefore made a complementary search for CO $J = 2$–1 emission, with a 21″ beam centered 3″ south of the bright peak in Figure 1. An upper limit of 25 mK was measured in a 1 km s$^{-1}$ spectral bin, which, for a thermalized gas excitation temperature of about 30 K, corresponds to a CO column density of $\leq 1.4 \times 10^{13}$ cm$^{-2}$. CO is subject to photodissociation by interstellar UV radiation, but accounting for this with standard models (van Dishoeck & Black 1988), the approximate column density of $H_2$ molecules is $\leq 2 \times 10^{20}$ cm$^{-2}$ ($A_V \leq 0.2$).

The total mass of gas and dust around $\epsilon$ Eri is estimated at less than an Earth mass. For the dust component alone, we find 0.005–0.02 $M_\oplus$ [(1.5–60) $\times 10^{-8}$ $M_\odot$], assuming $T_{\rm dust}$ of 30 K and an absorption coefficient $\kappa_\nu$ between 1.7 and 0.4 cm$^2$ g$^{-1}$. The lower value of $\kappa_\nu$ is suggested by models of large, icy grains (Pollack et al. 1994), while the higher estimate has been used for previous observations of Vega-type stars (see, e.g., Holland et al. 1998b). However, very large grains could dominate the mass while adding little emission, so both mass estimates are lower limits. The CO upper limit corresponds to $\leq 0.4$ $M_\oplus$ of molecular gas, when extrapolated over the area of dust emission above half-maximum brightness.

## 3. DISCUSSION

The 850 $\mu$m image shows extended emission, which most resembles a ring of dust around the star. The emission peaks at a radius of 18″ (≈60 AU), and substantially reduced emission is seen at about 30 AU. This ringlike morphology was previously suspected from single-beam observations at 1.3 mm, where flux variations were found with different beam sizes (Zuckerman & Becklin 1993), but is only now seen directly. The image also shows some surprising asymmetries and bright peaks, which are discussed below.

Figure 2 shows the azimuthally averaged radial profile calculated from the 850 $\mu$m map. There is a difference of a factor of 2 between the flux densities of the ring ($r = 18''$) and the cavity minimum ($r \approx 8''$). The cavity region out to this distance has only 6% of the total integrated flux. There is an apparent rise in flux density within $r = 4''.5$, which, in the unsmoothed data, appears to correspond to a small peak south of the star. However, the signal level in this region is uncertain, since it includes less than 10 map pixels.

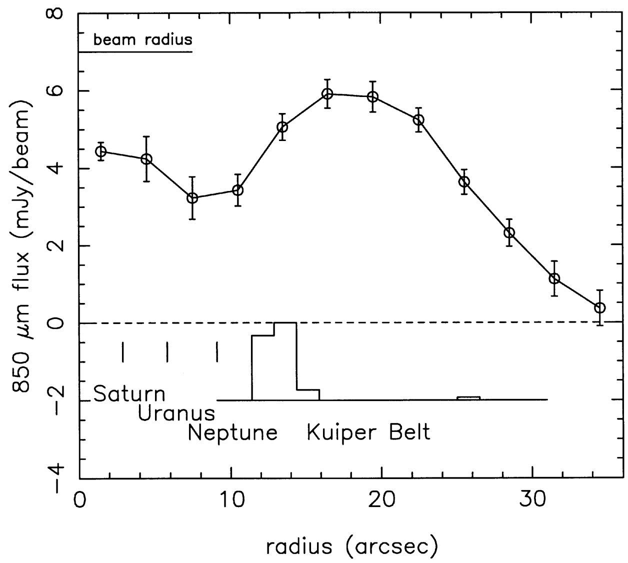


FIG. 2.—Radial profile of dust emission around $\epsilon$ Eri. The mean 850 $\mu$m flux density (in units of mJy beam$^{-1}$) is plotted against the radial distance from the star. The data are averaged in 3″ bins, to match the raw image sampling, and the error bars represent the standard error of the mean from the dispersion of signals at that radius. For comparison, the number of known Kuiper Belt objects is plotted underneath as a function of the semimajor axis, together with the locations of the outer planets.

The most probable explanation for the ringlike structure is a young analog of the Kuiper Belt. The central deficit of emission suggests an accumulation of dust into planetesimals (which emit much less per unit mass than individual grains do). The $\epsilon$ Eri system could thus be analogous to the young solar system, seen when planet formation is ongoing or complete, but some dust is still present at all radii out to about 36″ (115 AU). The age of the star is not well defined but can be estimated from the level of chromospheric activity. An age relation for dwarf stars is discussed by Soderblom, Duncan, & Johnson (1991), and their results for $\epsilon$ Eri (Soderblom & Däppen 1989) suggest an age of ≈0.5–1.0 Gyr. At this age, a partially cleared but still dusty system is seen, as expected.

Figure 2 also shows the locations of the solar outer planets and the Kuiper Belt,[8] sketched below the dust profile of $\epsilon$ Eri. The least dust emission is seen at the equivalent of Uranus' and Neptune's orbits, while the ring peaks at about 60 AU, well within the Kuiper Belt zone. Since the 850 $\mu$m image is broadened by the beam size of 15″, the dust ring must in fact be narrower than it appears in Figure 2. The observed width at half-maximum is from radii of 7″.5–27″, which, when deconvolved from the beam, imply half-maximum points at about 11″ and 23″, or 35–75 AU. This is similar to our solar system, since the Kuiper Belt has an inferred declining density outward from $r \approx 32$ AU (Jewitt & Luu 1995), with much of the population within 100 AU.

*IRAS* observations suggested considerable emission from the cavity region, with warm grains (50–370 K) inside 8″–11″ radius (Aumann 1991; Gillett 1986). At 850 $\mu$m, this inner region

[8] See http://www.ifa.hawaii.edu/faculty/jewitt/kb.html, maintained by D. Jewitt at the Institute for Astronomy at the University of Hawaii.

contributes only ∼9% of the flux, and for the higher $T_{dust}$, it contributes less than 5% of the overall mass. Thus, there is a genuine cavity within the ring, although it does contain some grains. In fact, the inner region is much dustier than the Sun's zodiacal belt, by 2–3 orders of magnitude (Zuckerman & Becklin 1993). This persistence of central material around $\epsilon$ Eri at 0.5–1.0 Gyr is consistent with the history of the solar system, where the Earth was heavily bombarded by asteroids up to about 0.6 Gyr (Maher & Stevenson 1988).

Other mechanisms can reduce the amount of dust emission near a star, including grain mantle sublimation or radiation-grain drag (the Poynting-Robertson [P-R] effect). However, ice mantles should persist to within a few AU of $\epsilon$ Eri, since the giant planets in the solar system are believed to have formed around rock and ice cores, and the luminosity of $\epsilon$ Eri is only about 0.33 $L_{\odot}$ (Soderblom & Däppen 1989). For P-R drag, grains ∼1 mm in diameter would have been cleared only to radii of about 15 AU (Jura 1990), even if the star is as old as 1 Gyr. Thus, it would be difficult to reproduce the clearing out to the observed 35 AU. Also, P-R drag naturally produces a $1/r$ density distribution as small grains spiral in toward the star, and this is not seen. Thus, it appears unlikely that sublimation of grain mantles or radiation-grain drag can explain the reduced emission close to $\epsilon$ Eri.

The total mass of the $\epsilon$ Eri ring depends on the presence of gas but is at least ∼0.01 $M_{\oplus}$ and possibly as high as 0.4 $M_{\oplus}$. This range encompasses the present-day mass of comets in the Kuiper Belt, ≈0.04–0.3 $M_{\oplus}$ between 30 and 100 AU (Backman, Dasgupta, & Stencel 1995). The $\epsilon$ Eri circumstellar ring therefore could be evolving into a Kuiper Belt analog of icy cometary bodies. Comets may form in only a few $10^5$ yr (Weidenschilling 1997), but the time to accrete and/or disperse all the dust is likely to be $\gg 10^8$ yr, which is the period estimated to form large Kuiper Belt objects (Kenyon & Luu 1998).

The $\epsilon$ Eri ring system appears close to face-on, since the morphology is roughly circular (Fig. 1). The major/minor axis ratio is ∼1.1 (66″ and 60″ diameters at the 3 $\sigma$ level), implying an inclination to the plane of the sky of $i \sim 25°$. This is in good agreement with the orientation of $i \approx 30° \pm 15°$ deduced for the stellar pole from optical line data (Saar & Osten 1997). These results suggest that the dust ring is aligned with the stellar equator.

A surprising result is the nonuniformity of the ring (Fig. 1). The bright peak seen at ($d$R.A., $d$decl.) = (+19″, −7″) has a flux density of 6.9 mJy in a 15″ beam area, compared with the region on the opposite side of the star where the flux density is only 3.5 mJy beam$^{-1}$, a difference of 5 times the rms noise. The bright peak is a real feature (identified in 13 out of 16 of the individual maps). The fainter peaks northeast and southwest of the star are less certain, since they were identified in only half of the individual maps.

An enhancement of dust density might represent the wake of a planet orbiting within the ring. Dust can become trapped in resonant orbits with a planet, and for example, Dermott et al. (1994) found that up to 20% of the zodiacal dust near the Earth is trapped to form a dust condensation, which is seen in *IRAS* data. Alternatively, a planet orbiting just inside the $\epsilon$ Eri ring could cause transient features, similar to the manner in which Neptune "erodes" the inner edge of the Kuiper Belt (Jewitt & Luu 1995). Asymmetries can also be produced when the peculiar velocity of the star with respect to the interstellar medium causes interstellar grains to stream into the disk, and erosion effects produce a brightness change on one side (Artymowicz & Clampin 1997). This process is likely to be effective only at very large radii (hundreds of AU). Finally, Backman & Paresce (1993) have pointed out that planetesimal collision rates are low at a few tens of AU; thus, recent collisions will produce discontinuous features. The flux enhancement at (+19″, −7″) is 2.6 mJy, or the amount of dust that would be produced by the destruction of a body with 15%–55% of the mass of Pluto (for $T_{dust}$ = 30 K, $\kappa_{\nu}$ = 1.7–0.4 cm$^{-2}$ g$^{-1}$). However, it is unlikely that we would observe such a major collision, since the remnants would disperse within a few orbital periods (500 yr at 60 AU) or a fraction less than $10^{-5}$ of the age of the system.

## 4. CONCLUSIONS

A dust ring has been detected around $\epsilon$ Eri with a mass and radius similar to the Kuiper Belt. Dust appears to be partially cleared inside the ring, which is consistent with accumulation into planetesimals. Other mechanisms for producing decreased dust emission cannot be definitively ruled out, but Poynting-Robertson drag and grain mantle sublimation appear unlikely to produce such a cavity. An inhomogeneity in the ring suggests the presence of a large orbiting body, either within the ring or just inside it. This corresponds to an orbit similar to Neptune's or up to twice as large.

Any planet formation around $\epsilon$ Eri is probably complete, since the stellar age is around 0.5–1.0 Gyr, and Earth-like planets are believed to form within 0.1 Gyr (gas giants on shorter timescales). No direct evidence has as yet been found for planets around $\epsilon$ Eri. Indications of a 10 yr variation in radial velocity (Walker et al. 1995) are now suspected to be a multiple of a 5 yr period in changes in the stellar photosphere (Gray & Baliunas 1995). The amplitude of the suspected radial velocity was ∼15 m s$^{-1}$, and more recent searches (G. Marcy 1998, private communication) find no such effect, with errors of 10–15 m s$^{-1}$ over a 10 yr period. However, the radial velocities will be reduced because the $\epsilon$ Eri system is seen almost face-on, making it harder to detect Jovians by this method. The new submillimeter image suggests that the $\epsilon$ Eri system is a strong candidate for an analog of the young solar system and that renewed planetary searches by various techniques could be rewarding.

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## REFERENCES

Artymowicz, P., & Clampin, M. 1997, ApJ, 490, 863
Aumann, H. H. 1988, AJ, 96, 1415
———. 1991, in The Infrared Spectral Region of Stars, ed. C. Jaschek & Y. Andrillat (Cambridge: Cambridge Univ. Press), 363
Aumann, H. H., et al. 1984, ApJ, 278, L23
Backman, D. E., Dasgupta, A. A., & Stencel, R. E. 1995, ApJ, 450, L35
Backman, D. E., & Paresce, F. 1993, in Protostars and Planets III, ed. E. H. Levy & J. I. Lunine (Tucson: Univ. Arizona Press), 1253
Carter, B. S. 1990, MNRAS, 242, 1
Chini, R., Krügel, E., & Kreysa, E. 1990, A&A, 227, L5
Chini, R., Krügel, E., Kreysa, E., Shustov, B., & Tutukov, A. 1991, A&A, 252, 220

Dent, W. R. F., Greaves, J. S., Mannings, V., Coulson, I. M., & Walther, D. M. 1995, MNRAS, 277, L25
Dermott, S. F., Jayarama, S., Xu, Y. L., Gustaffson, B. A. S., & Liou, J. C. 1994, Nature, 369, 719
Fischer, O., & Pfau, W. 1997, A&A, 325, 551
Gillett, F. C. 1986, in Light on Dark Matter, ed. F. P. Israel (Dordrecht: Reidel), 61
Gray, D. F., & Baliunas, S. L. 1995, ApJ, 441, 436
Holland, W. S., Cunningham, C. R., Gear, W. K., Jenness, T., Laidlaw, K., Lightfoot, J. F., & Robson, E. I. 1998a, Proc. SPIE, in press
Holland, W. S., et al. 1998b, Nature, 392, 788
Jayawardhana, R., Fisher, S., Hartmann, L., Telesco, C., Pina, R., & Fazio, G. 1998, ApJ, 503, L79
Jenness, T., & Lightfoot, J. F. 1998, in ASP Conf. Ser. 145, Astronomical Data Analysis Software and Systems VII, ed. R. Albrecht, R. N. Hook, & H. A. Bushouse (San Francisco: ASP), 216
Jenness, T., Lightfoot, J. F., & Holland, W. S. 1998, Proc. SPIE, in press
Jewitt, D., & Luu, J. 1995, AJ, 109, 1867
Jura, M. 1990, ApJ, 365, 317
Kenyon, S. J., & Luu, J. 1998, AJ, 115, 2136
Koerner, D. W., Ressler, M. E., Werner, M. W., & Backman, D. E. 1998, ApJ, 503, L83
Maher, K. A., & Stevenson, D. J. 1988, Nature, 331, 612
Marcy, G. W., Butler, R. P., Williams, E., Bildsten, L., Graham, J. R., Ghez, A. M., & Jernigan, J. G. 1997, ApJ, 481, 926
Mayor, M., & Queloz, D. A. 1995, Nature, 378, 355
Pollack, J. B., Hollenbach, D., Beckwith, S., Simonelli, D. P., Roush, T., & Fong, W. 1994, ApJ, 421, 615
Saar, S. H., & Osten, R. A. 1997, MNRAS, 284, 803
Smail, I., Ivison, R. J., & Blain, A. W. 1997, ApJ, 490, L5
Smith, B. A., & Terrile, R. J. 1984, Science, 226, 1421
Soderblom, D. R., & Däppen, W. 1989, ApJ, 342, 945
Soderblom, D. R., Duncan, D. K., & Johnson, D. R. H. 1991, ApJ, 375, 722
van Dishoeck, E. F., & Black, J. H. 1988, ApJ, 334, 771
Walker, G. A. H., Walker, A. R., Irwin, R. A., Larson, A. M., Yang, S. L. S., & Richardson, D. C. 1995, Icarus, 116, 359
Walker, H. J., & Wolstencroft, R. D. 1988, PASP, 100, 1509
Weidenschilling, S. J. 1997, Icarus, 127, 290
Zuckerman, B., & Becklin, E. E. 1993, ApJ, 414, 793
Zuckerman, B., Forveille, T., & Kastner, J. 1995, Nature, 373, 494