

## A POSSIBLE MASSIVE ASTEROID BELT AROUND $\zeta$ LEPORIS

C. H. CHEN AND M. JURA

Department of Physics and Astronomy, University of California at Los Angeles, Los Angeles,  
CA 90095-1562; cchen@astro.ucla.edu, jura@clotho.astro.ucla.edu

Received 2001 June 18; accepted 2001 September 13; published 2001 September 28

### ABSTRACT

We have used the Keck I telescope to image at 11.7 and 17.9  $\mu\text{m}$  the dust emission around  $\zeta$  Leporis, a main-sequence A-type star at 21.5 pc from the Sun with an infrared excess. The excess is at most marginally resolved at 17.9  $\mu\text{m}$ . The dust distance from the star is probably  $\leq 6$  AU, although some dust may extend to 9 AU. The mass of observed dust is  $\sim 10^{22}$  g. Since the lifetime of dust particles is about  $10^4$  yr because of the Poynting-Robertson effect, we robustly estimate at least  $4 \times 10^{26}$  g must reside in parent bodies, which may be asteroids if the system is in a steady state and has an age of  $\sim 300$  Myr. This mass is approximately 200 times that contained within the main asteroid belt in our solar system.

*Subject headings:* circumstellar matter — planetary systems — stars: individual (HR 1998)

### 1. INTRODUCTION

Vega-like systems, first discovered by *IRAS*, are main-sequence stars surrounded by dust. The operation of the Poynting-Robertson effect on micron-sized grains, responsible for much of the observed infrared excess, requires that the lifetime of these particles be significantly shorter than the age of the stars (Backman & Paresce 1993). Thus, the dust grains must be replenished from a reservoir such as collisions between larger bodies or the sublimation of comets. Studies of Vega-like systems thus afford the opportunity to study the evolution of large solids such as planets, comets, and asteroids.

The identification of dust around main-sequence A-type stars is usually made from the *IRAS* colors (e.g., Mannings & Barlow 1998; Silverstone 2000). Identifying objects with 12  $\mu\text{m}$  excess is difficult because the photosphere usually dominates the total flux at this wavelength. The bulk of the dust associated with main-sequence A-type stars typically has temperatures  $T_{\text{gr}} \sim 100$  K and semimajor axes greater than 50 AU. For example, imaging of HR 4796A (A0 V; distance from Earth 67.1 pc) in thermal infrared (Koerner et al. 1998; Jayawardhana et al. 1998) and in near-infrared scattered light (Schneider et al. 1999) revealed a dust ring with radius 70 AU, a distance scale similar to that of the Sun's Kuiper Belt.

Dust grains located  $\sim 5$  AU from a main-sequence A-type stars have  $T_{\text{gr}} \approx 300$  K, producing strong 12  $\mu\text{m}$  excesses. Searches for 12  $\mu\text{m}$  excesses around main-sequence stars have revealed that 300 K dust around A–K dwarfs is rare. In a survey of 548 A–K dwarfs, Aumann & Probst (1991) were able to identify *IRAS* 12  $\mu\text{m}$  excesses only with  $\beta$  Pictoris and  $\zeta$  Lep (=HR 1998 = HD 38678). Similarly, Coté (1987) derived unusually high temperatures for the dust around  $\zeta$  Lep compared to other Vega-like main-sequence stars from *IRAS* 12, 25, and 60  $\mu\text{m}$  observations. Although coronagraphic images of  $\beta$  Pic (Kalas & Jewitt 1995) have revealed a massive dust disk that extends to a radius of almost 1000 AU, no extended disk has been discovered around  $\zeta$  Lep. We have carried out a high-resolution mid-infrared imaging study to learn about the dust properties and the origin and evolution of the dust around  $\zeta$  Lep.

The star  $\zeta$  Lep is a main-sequence A3 Vn star with a *Hipparcos* distance of 21.5 pc and a fractional dust luminosity,  $L_{\text{IR}}/L_* = 1.7 \times 10^{-4}$  (Fajardo-Acosta, Telesco, & Knacke 1998). It has been identified as a member of the Castor moving

group, which also contains Fomalhaut and Vega, based on its kinematic properties (Barrado y Navascués 1998). Barrado y Navascués (1998) estimates its age to be between 100 and 400 Myr from the lithium abundance of later type stars in the Castor moving group and from the space motion of the group. Recently, Song et al. (2001) estimated an age of 50–350 Myr using Stromgren *uvby* $\beta$  photometry corrected for the effects of rapid rotation, to determine stellar parameters (effective temperature  $T_{\text{eff}}$ , surface gravity  $g$ , and metallicity), which then are fit to stellar evolutionary tracks of Schaller et al. (1992). Lachaume et al. (1999) fit the position of  $\zeta$  Lep on the H-R diagram with theoretical isochrones of Bertelli et al. (1994) and estimate a slightly older age of 200–500 Myr.

### 2. OBSERVATIONS

Our data were obtained on the night of 2001 February 5 (UT) at the Keck I telescope using the Long Wavelength Spectrometer (LWS), which was built by a team led by B. Jones and is described on the Keck Website. The LWS uses a  $128 \times 128$  SiAs BIB array with a scale at the Keck telescope of  $0''.08$  pixel $^{-1}$  and a total field of view of  $10''.2 \times 10''.2$ . We used the “chop-nod” mode of observing and two different filters: 11.2–12.2 and 16.9–18.9  $\mu\text{m}$ . We used Capella ( $\alpha$  Aur) for flux and point-spread function calibrations. The data were reduced at the University of California at Los Angeles using standard LWS routines.

We flux-calibrate our data using the results for Capella that  $F_{\nu}(11.5 \mu\text{m}) = 176.1$  Jy and  $F_{\nu}(19.3 \mu\text{m}) = 67.5$  Jy (Gezari, Schmitz, & Mead 1987) extrapolated to our bands assuming that  $F_{\nu} \propto \nu^2$  between 10 and 20  $\mu\text{m}$ . For  $\zeta$  Lep, we find  $F_{\nu}(11.7 \mu\text{m}) = 1.60 \pm 0.20$  Jy and  $F_{\nu}(17.9 \mu\text{m}) = 0.93 \pm 0.07$  Jy, in agreement with previous observations by Fajardo-Acosta et al. (1998). We conservatively estimate the uncertainties associated with our measurements from the drift in the flux of Capella before and after our observations of  $\zeta$  Lep. Since less time elapsed between our observations of the standard star at 17.9  $\mu\text{m}$ , the percentage errors are smaller at this wavelength.

Determining the infrared excess of  $\zeta$  Lep requires subtracting a model for the stellar photosphere from the observed fluxes. We model the spectral energy distribution (SED) of  $\zeta$  Lep with a 1993 Kurucz stellar atmosphere, assuming solar metallicity ( $[Z/H] = 0.0$ ). We assume no interstellar extinction because

the star is only 21.5 pc from the Sun. We assume negligible circumstellar extinction since  $L_{\text{IR}}/L_* \sim 10^{-4}$ , and we have no evidence in our data for an edge-on system. We find a best fit (minimum  $\chi^2$ ) for the following parameters: stellar effective temperature  $T_{\text{eff}} = 8500$  K and surface gravity  $\log g = 4.5$  (see Fig. 1). With this fit, we find photospheric fluxes of  $F_{\nu}(11.7 \mu\text{m}) = 1.24 \pm 0.01$  Jy and  $F_{\nu}(17.9 \mu\text{m}) = 0.53 \pm 0.01$  Jy; thus, we find 11.7 and 17.9  $\mu\text{m}$  excesses of  $0.36 \pm 0.2$  and  $0.40 \pm 0.07$  Jy, respectively.

We convolve models for the dust distribution with the point-spread function (PSF) of Capella at 17.9  $\mu\text{m}$  to estimate the maximum distance of the dust from the star. Observations of Capella made 40 minutes before, 20 minutes after, and 100 minutes after our observations of  $\zeta$  Lep varied somewhat. We use the PSF measured closest in time to our observations of  $\zeta$  Lep to construct our analysis. We assume the dust is confined to a face-on ring, with an average distance of  $0''.10$ ,  $0''.24$ , or  $0''.40$  from the star and a width ranging between  $0''.20$  and  $0''.24$ , and that 55% of the power is emitted by the point source and 45% of the power is emitted by the ring, consistent with our model for the photosphere and the total flux measured from  $\zeta$  Lep (see Fig. 2). We find a best fit for the model with the smallest dust disk (average radius  $0''.10$ ). The models including larger disks do not fit the surface brightness for the central pixel or the surface brightnesses for the outer pixels well. Thus, we estimate a maximum dust distance of 6 AU from the star. When models for the dust distribution are convolved with the PSF from earlier or later in the evening, the dust could extend as far as 9 AU from the star.

### 3. DUST PROPERTIES

#### 3.1. Minimum Grain Distance

The minimum grain distance can be constrained from the temperature of the grains assuming that they are blackbodies. We estimate a grain temperature of 320 K from the ratio of the 11.7  $\mu\text{m}$  excess to the 17.9  $\mu\text{m}$  excess. Blackbodies in radiative equilibrium with a stellar source are located a distance

$$D = \frac{1}{2} \left( \frac{T_*}{T_{\text{gr}}} \right)^2 R_* \quad (1)$$

from the central star (Jura et al. 1998), where  $T_*$  and  $R_*$  are the effective temperature of the stellar photosphere and the stellar radius. We estimate the stellar luminosity from the bolometric magnitude using the *Hipparcos* V-band magnitude ( $m_V = 3.55$  mag) and distance (21.5 pc) and a bolometric correction (Flower 1996) corresponding to an effective temperature  $T_{\text{eff}} = 8500$  K. For  $\zeta$  Lep, we find a stellar luminosity  $L_* = 14 L_{\odot}$ . The stellar radius is therefore  $R_* = 1.7 R_{\odot}$ . From equation (1) and the stellar properties summarized in Table 1, we find a minimum grain distance of 2.8 AU.

We can additionally infer the dust temperature and distance by fitting a blackbody to the mid-infrared fluxes reported for wavelengths longer than 10  $\mu\text{m}$ . We find a best fit (minimum  $\chi^2$ ) for the photosphere-subtracted fluxes for  $T_{\text{dust}} = 230$  K and  $D = 5.4$  AU, consistent with our observations.

#### 3.2. Circumstellar Dust Grain Size

A lower limit to the size of dust grains orbiting a star can be found by balancing the force due to radiation pressure with the force due to gravity. For small grains with radius  $a$ , the

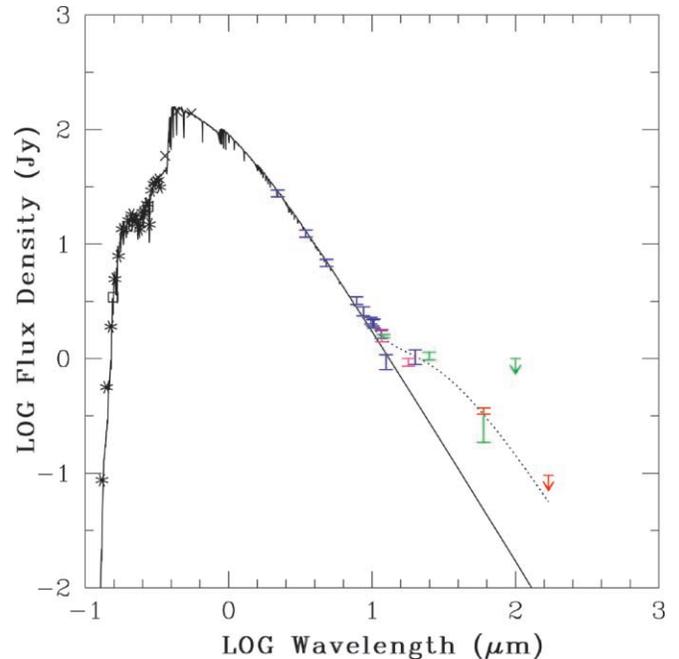


FIG. 1.—SED for  $\zeta$  Lep with ultraviolet fluxes from *TD-1* (Thompson et al. 1978) plotted as squares, from *IUE* plotted as asterisks, and from *UBV* photometry (Cousins 1984) plotted as crosses. Previous *JHK* and mid-infrared photometry from the Infrared Telescope Facility (IRTF; Fajardo-Acosta et al. 1998) are shown with dark blue error bars, from the IRAF Faint Source Catalog (Moshir et al. 1989) with green error bars, and from the *Infrared Space Observatory* (Habing et al. 2001) with red error bars. Our 11.7 and 17.9  $\mu\text{m}$  photometry, as reported here, is shown with magenta error bars. Overlaid is a 1993 Kurucz model for a stellar atmosphere with  $T_{\text{eff}} = 8500$  K, surface gravity  $\log g = 4.5$ , and solar metallicity ( $[Z/H] = 0.0$ ) plotted to minimize  $\chi^2$ . The dotted black line is a best fit to the mid-infrared fluxes at wavelengths longer than 10  $\mu\text{m}$  assuming a single-temperature blackbody ( $T = 230$  K) plus the stellar photosphere.

force due to radiation pressure overcomes gravity for

$$a < 3L_* Q_{\text{pr}} / 16\pi GM_* c \rho_s \quad (2)$$

(Artymowicz 1988), where  $L_*$  and  $M_*$  are the stellar luminosity and mass,  $Q_{\text{pr}}$  is the radiation pressure coupling coefficient, and  $\rho_s$  is the density of an individual grain. Since radiation from an A-type star is dominated by optical and ultraviolet light, we expect that  $2\pi a/\lambda \gg 1$ , and therefore the effective cross section of the grains can be approximated by their geometric cross section so  $Q_{\text{pr}} \approx 1$ . Based on  $T_{\text{eff}}$  and  $L_*$ , the inferred stellar mass is  $1.9 M_{\odot}$  (Siess, Dufour, & Forestini 2000). With  $\rho_s = 2.5 \text{ g cm}^{-3}$ , the minimum radius for grains orbiting  $\zeta$  Lep is  $a = 1.7 \mu\text{m}$ .

We can estimate the average size of the grains assuming a size distribution for the dust grains. Analogous to the main asteroid belt in our solar system and as expected from equilibrium between production and destruction of objects through collisions (Greenberg & Nolan 1989), we assume

$$n(a)da = n_0 a^{-p} da, \quad (3)$$

with  $p \approx 3.5$  (Binzel, Hanner, & Steel 2000). If we assume a minimum grain radius of 1.7  $\mu\text{m}$ , we find an average grain radius  $\langle a \rangle = 2.8 \mu\text{m}$ , if we weight by the number of particles.

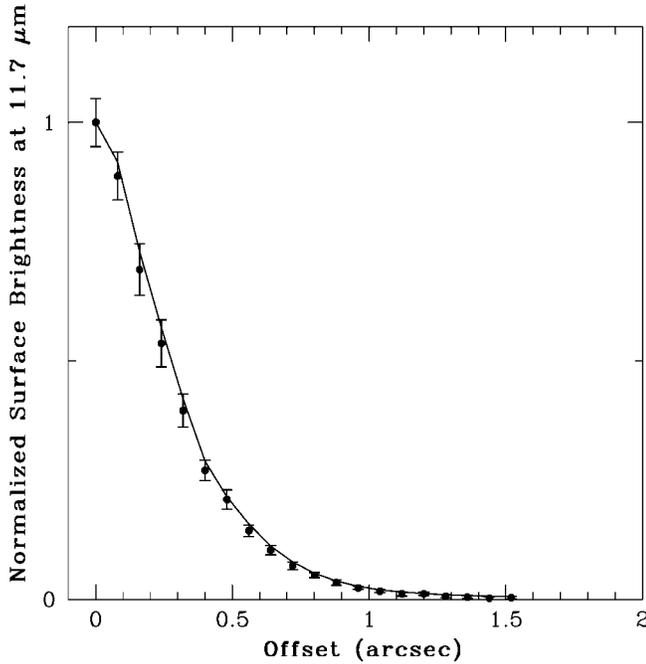


FIG. 2a

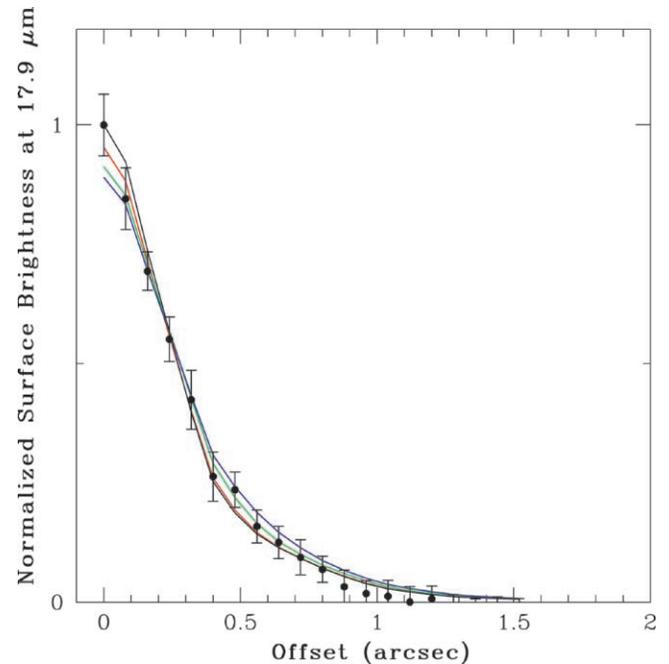


FIG. 2b

FIG. 2.—(a) Radial profile for  $\zeta$  Lep [ $\alpha(\text{J2000.0}) = 05^{\text{h}}46^{\text{m}}57^{\text{s}}$ ,  $\delta(\text{J2000.0}) = -19^{\circ}49'19''$ ] at  $11.7 \mu\text{m}$ . The solid black line is the PSF for the standard star Capella [ $\alpha(\text{J2000.0}) = 05^{\text{h}}16^{\text{m}}41^{\text{s}}$ ,  $\delta(\text{J2000.0}) = +45^{\circ}59'53''$ ] normalized to the observations of  $\zeta$  Lep, while the error bars show the azimuthally averaged data for  $\zeta$  Lep. (b) Radial profile for  $\zeta$  Lep at  $17.9 \mu\text{m}$ . The solid black line is the PSF for the standard star Capella, normalized to the observations of  $\zeta$  Lep, while the error bars show the azimuthally averaged data for  $\zeta$  Lep. The colored lines are best-fit models (minimum  $\chi^2$ ) for the spatial extent of the dust convolved with the PSF of Capella. The red, green, and blue models assume a central point source and a ring with average angular radius  $0''.10$ ,  $0''.24$ , and  $0''.40$ , respectively. The  $\chi^2$ -values for the different curves here are 4.5, 5.2, and 9.3. In each model, 55% of the power is emitted by the point source and 45% of the power is emitted by the ring, consistent with our model for the photosphere and the total flux emitted from  $\zeta$  Lep.

### 3.3. Mass of Circumstellar Dust around $\zeta$ Lep

We can estimate the minimum mass of dust around  $\zeta$  Lep assuming that the particles have  $\langle a \rangle \sim 2.8 \mu\text{m}$ ; if the grains are larger, then our estimate is a lower bound. If we assume a thin shell of dust at distance  $D$  from the star, and if the particles are spheres of radius  $a$ , and if the cross section of the particles equals their geometric cross section, then the mass of dust is

$$M_d \geq \frac{16}{3} \pi \frac{L_{\text{IR}}}{L_*} \rho_s D^2 \langle a \rangle \quad (4)$$

(Jura et al. 1995), where  $L_{\text{IR}}$  is the luminosity of the dust. If  $D = 6 \text{ AU}$ ,  $\rho_s = 2.5 \text{ g cm}^{-3}$ , and  $\langle a \rangle = 2.8 \mu\text{m}$ , then  $M_d = 1.6 \times 10^{22} \text{ g}$ .

TABLE 1  
 $\zeta$  LEP PROPERTIES

Quantity	Adopted Value	Reference
Spectral type .....	A3 Vn	1
Distance .....	21.5 pc	2
Effective temperature ( $T_{\text{eff}}$ ) .....	8500 K	
Surface gravity ( $\log g$ ) .....	4.5	
Stellar radius ( $R_*$ ) .....	$1.7 R_{\odot}$	
Stellar luminosity ( $L_*$ ) .....	$14 L_{\odot}$	
Rotational velocity ( $v \sin i$ ) .....	$202 \text{ km s}^{-1}$	1
Fractional dust luminosity ( $L_{\text{IR}}/L_*$ ) .....	$1.7 \times 10^{-4}$	
Age .....	50–500 Myr	3, 4, 5

REFERENCES.—(1) Hoffleit & Warren 1991; (2) *Hipparcos*; (3) Barrado y Navac es 1998; (4) Lachaume et al. 1999; (5) Song et al. 2001.

### 3.4. Lifetime of Circumstellar Grains

One mechanism that may remove particles is Poynting-Robertson drag. The Poynting-Robertson lifetime of grains in a circular orbit, a distance  $D$  from a star, is

$$t_{\text{PR}} = \frac{4\pi \langle a \rangle \rho_s c^2 D^2}{3 L_*} \quad (5)$$

(Burns, Lamy, & Soter 1979). With the parameters given above and  $L_* = 14 L_{\odot}$ , the Poynting-Robertson lifetime of the grains is  $t_{\text{PR}} = 1.3 \times 10^4 \text{ yr}$ . Since this timescale is significantly shorter than the stellar age ( $t_{\text{age}}$ ), we hypothesize that the grains are replenished through collisions between larger bodies. By analogy with the solar system, we propose that the parent bodies are asteroids.

### 3.5. Mass of the Parent Bodies

We can estimate the total mass contained in parent bodies around  $\zeta$  Lep assuming a steady state. If  $M_{\text{PB}}$  denotes the mass in parent bodies, then we may write

$$M_{\text{PB}} \geq \frac{M_d}{t_{\text{PR}}} t_{\text{age}} \quad (6)$$

With  $M_d = 1.6 \times 10^{22} \text{ g}$ ,  $t_{\text{PR}} = 1.3 \times 10^4 \text{ yr}$ , and  $t_{\text{age}} = 300 \times 10^6 \text{ yr}$ , we estimate a total mass of parent bodies  $\sim 4 \times 10^{26} \text{ g}$ , approximately 200 times the mass of the main asteroid belt in our solar system (Binzel et al. 2000). From

equations (4) and (5), we find

$$M_{\text{PB}} \geq \frac{4L_{\text{IR}}t_{\text{age}}}{c^2}. \quad (7)$$

Since  $L_{\text{TR}}$  is well measured, our estimate for the lower limit on the mass of parent bodies,  $M_{\text{PB}}$ , is better constrained than our estimate for the mass of observed dust.

#### 4. DISCUSSION

The star  $\zeta$  Lep is distinctive because the dust around it is warm and close compared to the dust in other well-known debris disk systems:  $\beta$  Pictoris, HR 4796A, Vega, and Fomalhaut. We can quantify this difference by comparing the ratios of 60  $\mu\text{m}$  excess to the 25  $\mu\text{m}$  excess. For  $\zeta$  Lep, this ratio is at least a factor of 2 smaller than for any of the other stars considered (see Table 2).

The lack of dust at distances greater than 6 AU raises the possibility of the presence of a planet, sculpting the disk and confining the dust. Such a planet could increase the eccentricity of the orbits of the putative asteroids and thus drive them into mutual collisions to produce the observed dust.

#### 5. CONCLUSIONS

We have obtained high-resolution mid-infrared images of  $\zeta$  Lep at 11.7 and 17.9  $\mu\text{m}$  using the LWS on the Keck I telescope and conclude the following:

1. The star  $\zeta$  Lep possess a strong mid-infrared excess, which is at most marginally resolved, and thus surrounding

TABLE 2  
DISK PROPERTIES

Star	Photosphere + Excess [ $F_{\nu}(60 \mu\text{m})/F_{\nu}(25 \mu\text{m})$ ] <sup>a</sup>	Excess [ $F_{\nu}(60 \mu\text{m})/F_{\nu}(25 \mu\text{m})$ ] <sup>b</sup>	$T_{\text{color}}$ <sup>c</sup> (K)
$\zeta$ Lep .....	0.32	0.30	370 <sup>d</sup>
$\beta$ Pic .....	2.2	2.3	100
HR 4796A .....	2.2	1.8	110
Vega .....	0.85	4.4	80
Fomalhaut .....	2.0	11	70

<sup>a</sup> *IRAS* data without color corrections.

<sup>b</sup> *IRAS* data with color corrections and photospheric subtraction.

<sup>c</sup> Derived from  $F_{\nu}(60 \mu\text{m})/F_{\nu}(25 \mu\text{m})$  for the excess radiation given in the previous column.

<sup>d</sup> A blackbody plus stellar photosphere fit to all of the fluxes reported for wavelengths greater than 10  $\mu\text{m}$  yields a lower temperature,  $T_{\text{gr}} = 230$  K.

dust probably lies within 6 AU although some dust may extend as far as 9 AU. This result is consistent with the temperature of the grains derived from the mid-infrared photometry.

2. Since the estimated Poynting-Robertson lifetime of grains with  $\langle a \rangle = 2.7 \mu\text{m}$  is  $1.3 \times 10^4$  yr, significantly shorter than the age of  $\zeta$  Lep, the grains must be replenished from a reservoir such as collisions between larger bodies, perhaps asteroids. For  $\zeta$  Lep, we robustly estimate that the minimum mass of parent bodies is  $\sim 4 \times 10^{26}$  g assuming that the system is in a steady state. This mass is approximately 200 times the mass of the Sun's main asteroid belt.

This work has been supported by funding from NASA. We thank M. Sykes, A. Weinberger, and B. Zuckerman for their comments.

#### REFERENCES

- Artymowicz, P. 1988, *ApJ*, 335, L79  
Aumann, H. H., & Probst, R. G. 1991, *ApJ*, 368, 264  
Backman, D. E., & Paresce, F. 1993, in *Protostars and Planets III*, ed. E. Levy & J. I. Lunine (Tucson: Univ. Arizona Press), 1253  
Barrado y Navascués, D. 1998, *A&A*, 339, 831  
Bertelli, G., Bressan, A., Chiosi, C., Fagotto, F., & Nasi, E. 1994, *A&AS*, 106, 275  
Binzel, R. P., Hanner, M. S., & Steel, D. I. 2000, in *Allen's Astrophysical Quantities*, ed. A. N. Cox (New York: Springer), 315  
Burns, J. A., Lamy, P. L., & Soter, S. 1979, *Icarus*, 40, 1  
Coté, J. 1987, *A&A*, 181, 77  
Cousins, A. J. W. 1984, *South African Astron. Obs. Circ.*, 8, 59  
Fajardo-Acosta, S. B., Telesco, C. M., & Knacke, R. F. 1998, *AJ*, 115, 2101  
Flower, P. J. 1996, *ApJ*, 469, 355  
Gezari, D., Schmitz, M., & Mead, J. M. 1987, *Catalog of Infrared Observations, Part II, Appendixes (Greenbelt: NASA)*  
Greenberg, R., & Nolan, M. C. 1989, in *Asteroids II*, ed. R. P. Binzel, T. Gehrels, & M. S. Matthews (Tucson: Univ. Arizona Press), 778  
Habing, H. J., et al. 2001, *A&A*, 365, 545  
Hoffleit, D., & Warren, W. H. 1991, *The Bright Star Catalogue* (5th ed.; New Haven: Yale Univ. Obs.)  
Jayawardhana, R., Fisher, S., Hartmann, L., Telesco, C., Piña, R., & Fazio, G. 1998, *ApJ*, 503, L79  
Jura, M., Ghez, A. M., White, R. J., McCarthy, D. W., Smith, R. C., & Martin, P. G. 1995, *ApJ*, 445, 451  
Jura, M., Malkan, M., White, R., Telesco, C., Pina, R., & Fisher, R. S. 1998, *ApJ*, 505, 897  
Kalas, P., & Jewitt, D. 1995, *AJ*, 110, 794  
Koerner, D. W., Ressler, M. E., Werner, M. W., & Backman, D. E. 1998, *ApJ*, 503, L83  
Lachaume, R., Dominik, C., Lanz, T., & Habing, H. J. 1999, *A&A*, 348, 897  
Mannings, V., & Barlow, M. J. 1998, *ApJ*, 497, 330  
Moshir, M., et al. 1989, *Explanatory Supplement to the IRAS Faint Source Survey (Pasadena: JPL)*  
Schaller, G., Schaerer, D., Meynet, G., & Maeder, A. 1992, *A&AS*, 96, 269  
Schneider, G., et al. 1999, *ApJ*, 513, L127  
Siess, L., Dufour, E., & Forestini, M. 2000, *A&A*, 358, 593  
Silverstone, M. D. 2000, Ph.D. thesis, Univ. California, Los Angeles  
Song, I., Caillault, J. P., Barrado y Navascués, D., & Stauffer, J. R. 2001, *ApJ*, 546, 352  
Thompson, G. I., Nandy, K., Jamar, C., Monfils, A., Houziaux, L., Carnochan, D. J., & Wilson, R. 1978, *Catalog of Stellar Ultraviolet Fluxes (ESA SR-28; Noordwijk: ESA)*