5

Zodiacal Dust in our Own and Other Planetary Systems

In our own and other solar systems, dust (very tiny solid particles composed of silicates, ices, and other minerals) is ever present. This material is both a remnant of the construction of the planets and a consequence of continuing collisions among comets, asteroids, and other small bodies. Even though this dust represents only a small fraction of the total mass of a system, its presence as many small particles makes it the most visible part of any planetary system viewed from a great distance. Indeed, looking from the Earth on a very dark night one can see after sunset a diffuse glow called the zodiacal light, which is sunlight scattered off of dust particles near the orbit of the Earth. This so-called zodiacal dust has two potentially serious impacts on the ability of TPF to detect and study Earth-like planets around other stars: First, the local zodiacal dust in our own solar system creates a diffuse glow at infrared wavelengths that hampers TPF's view of the sky, just as a city's lights hide the faintest stars from our gaze. Second, the exo-zodiacal dust around candidate stars contributes a glare that may partly or wholly mask orbiting planets from TPF's view (Angel, Cheng, and Woolf 1986). In the present chapter we review the current, imperfect, state of knowledge of the amount of dust around other stars and describe future observations that will provide more reliable information to aid in the final design of TPF.

A workshop on exo-zodiacal dust was held at the Ames Research Center in October 1997 (Backman *et al.* 1998). Some of the important findings of that workshop include:

- The conclusion that approximately 15% of stars of spectral types A, F, G, and K have significantly more (100× or more) cold dust than our own solar system has been confirmed, but not extended to significantly lower dust levels by the Infrared Space Observatory (ISO).
- The fact that only a handful of stars have warm, ~300 K dust, at a level of ~500× that of our solar system has been confirmed, but not extended to lower dust levels by ISO.

- The primary component of our cloud is debris from collisions of asteroids. Since models for formation of the solar system show formation of an asteroid belt only 50% of the time, there is reason to expect systems with the same amount or less dust as in our own solar system.
- The exo-zodiacal dust emission is expected to be smooth (less than 1% random variations) except for rings and wakes due to gravitational trapping by planets or bands due to recent asteroid or comet collisions.
- Photon noise and confusion effects will prevent TPF from detecting terrestrial planets with reasonably sized apertures when the level of dust emission in the target system exceeds by 5 to 10 times the level of emission in our own solar system.

THE LOCAL ZODIACAL CLOUD

Table 5.1 characterizes a “1 Zodi” dust cloud based on the properties of the dust in the vicinity of the Earth. A more detailed model of the local cloud is given in Appendix A based on data from the Infrared Astronomical Satellite (IRAS) and the Cosmic Background Explorer (COBE). One way to think of the magnitude of the zodiacal emission is to note that a patch of 1 Zodi cloud, 0.3 AU in diameter, emits roughly the same amount of radiation as the planet Earth. This is approximately true for both infrared thermal emission and optical scattered light because the dust has approximately the same reflectivity (“albedo”) and temperature as the Earth. An instrument working at 10 µm would need a 70 meter baseline to achieve 0.3 AU resolution at 10 pc and thus be able to distinguish a patch of zodiacal emission from a planet.

Dust sources. The dust in our solar system has three principal constituents: asteroidal and cometary debris and interstellar grains. The relative proportions of these components are poorly known and vary with position in the solar system. Because the level of exo-zodiacal emission is an important noise source for TPF (as discussed in Chapter 6 and Appendix A), it is important to determine the amount of dust in the habitable zones of TPF target stars, either by direct measurement or by well-constrained models of the various components of the exo-zodiacal dust.

Table 5.1. Illustrative Properties of a “1 Zodi” Cloud

Vertical Optical Depth at 1 AU	10^{-7}, decreasing with distance from the sun to at least the asteroid belt as r^{0} to $r^{-0.3}$
Surface Brightness at 1 AU	22 mag/arcsec^2 at 0.55 µm 25 MJy/sr at 12 µm (through the disk)
Grain Temperature	275 K, decreasing with distance from the sun as $r^{-0.4}$
Characteristic Grain Size	40 µm

Asteroid debris: Some, perhaps most, of the smooth zodiacal cloud is believed to come from the main asteroid belt via collisions and erosion of small asteroids. The Trojan asteroids (objects trapped in stable regions known as Lagrangian points ahead of and behind Jupiter in its orbit) may also be a source of debris near the Earth. The thermal emission near the ecliptic plane is enhanced in several symmetric bands, e.g. at ecliptic latitudes of ±1.4° and ±10°. These are identified as "families" of asteroid collision debris that drift past the Earth toward the sun from sources in the main asteroid belt. Further out in the solar system, the Kuiper Belt represents a collection of solid bodies beyond Neptune some hundreds of kilometers and smaller in size. The Kuiper belt can supply grains to the inner solar system via radiative drag due to sunlight, known as the Poynting-Robertson (PR) effect. However, for Kuiper Belt grains to contribute significantly to the inner solar system dust population they must survive collisions with interstellar grains and dynamical effects of the Jovian planets which can trap grains in resonances and/or eject them from the solar system.

Cometary debris: COBE data on the scale height of dust near the Earth indicates the presence of some local dust that is not distributed following the wedge of main belt asteroid debris and is thus probably cometary in origin. Extensive dust trails, discovered by IRAS, fill the orbits of periodic comets with mm-sized dust and meteors, which are eventually perturbed into the zodiacal dust cloud and sporadic meteor population.

Interstellar grains: The interstellar medium is expected to be a significant source of the smallest particles in the outer solar system. The Ulysses spacecraft detected impacts in that region coming in excess from the direction of solar motion. These are presumably interstellar grains (Grün *et al.* 1994; Mann and Hanner 1998).

Table 5.2 describes our knowledge of the relative strengths of the different sources of dust near the Earth. It is especially important to note in this context that planetesimal models of the formation of the planets produce an asteroid belt in only 50% of trials (Wetherill 1991). Thus, it seems possible to have a planetary system closely resembling ours but without an asteroid belt as a major source of terrestrial-temperature dust. Such a system would have a factor of 2 to 10 less zodiacal emission than our own solar system.

Table 5.2. Relative Strength of Sources of Zodiacal Dust Near the Earth

Main Belt Asteroid Collisions	50-90%
Comet Activity and Collisions	10-50%
Trojan Asteroids	minor
Kuiper Belt Planetesimals	minor
ISM Grains	~ 0.1%

Zodiacal Cloud Density Versus Time. Collisions of 10 km-radius bodies should occur in the main belt about every 10^7 years. One such collision could completely recreate the present zodiacal cloud. Because enhancements due to asteroid collisions survive for much longer than the PR time scale due to the continuous collisional erosion of the fragments, the overall state of the zodiacal cloud is determined by the combination of a number of collision families in various degrees of relaxation. A model history of the density in a single debris family shows a general decline as grains fall into the Sun due to PR drag, but punctuated by large transient increases due to subsequent collisions between fragments (Figure 5.1). The history of the zodiacal dust cloud over the age of the solar system is likely to have been closely connected to the history of the main asteroid belt. It is safe to state that the total mass of the asteroid population has steadily decreased and will continue to decrease due to planetary perturbations and collisions. A simple implication of this is that planet searches should be directed toward older stellar systems to avoid generally higher dust density. Figure 5.2 shows the limited amount of data available on the evolution of dust disks for stars of various ages. Observations from SIRTF, the Keck Interferometer, and the Large Binocular Telescope will help fill in plots like these as well as determine directly the cleanest systems for TPF to observe.

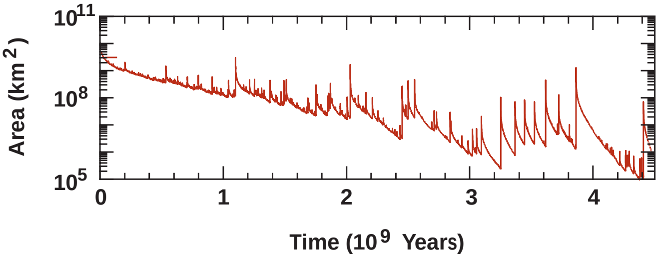

Figure 5.1. The surface area of the debris produced by the collision of two large asteroids at t=0 as a function of time (Dermott, private communication). The gradual decline is the result of grains falling into the sun as a result of Poynting-Robertson drag. Transients are due to subsequent collisions of large remnants producing sharply increased numbers of small grains.

Wakes And Other Signs Of Planets. Because of the resonant trapping of dust particles with small orbital eccentricities, the Earth is embedded in a ring of dust that co-revolves with the Earth around the Sun (Dermott *et al*. 1994; Reach *et al*. 1995; Figure 5.3a, b). The Earth resides in a cavity in this ring and a cloud of enhanced dust density permanently trails the Earth in its orbit. Dust trapped in the Earth's wake emits 10% of flux density of the Earth itself. Each planet in the solar system should have such a wake. While the presence of wakes and other resonant features are a problem for TPF, they also serve as signposts for planets that should be readily detectable at low resolution and angular sensitivity.

Simulations described in Chapter 6 indicate that TPF's ability to identify an Earth-like planet at 10 pc would be severely degraded if there were "random" exo-zodiacal brightness variations with 10% amplitude superimposed on a smooth cloud with more than about 10-Zodi density. Fortunately, outside of wakes and other resonant structures, the overall zodiacal cloud is expected to be relatively homogeneous because of the smoothing effect of the dissipative forces responsible for the cloud in the first place. Dermott *et al.* (1998) estimate that after subtraction of any systematic large-scale gradient, the departures from

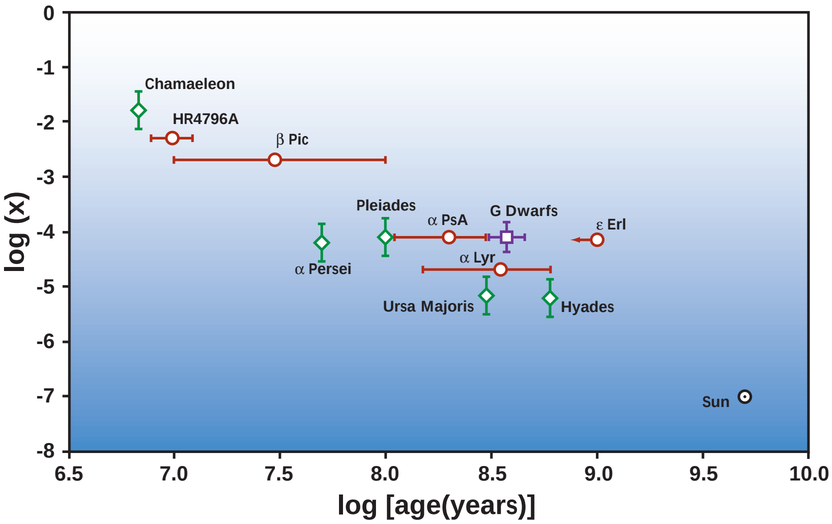

Figure 5.2. The ratio of dust disk to stellar luminosity is plotted as a function of age for a number of stars, ranging from young pre-main sequence objects to the Sun (Becklin et al. 1999). While the number of stars in the sample is small, the apparent decrease in the amount of dust in a disk with age suggests that searches for terrestrial planets should concentrate on older stars.

the average brightness should be less than 1% from one ~AU-sized patch to the next. Simulations show that this level of inhomogeneity does not affect the noise level for planet detection.

Possible Self-Limitation of Zodiacal Cloud Density. Theoretical calculations (Lagrange *et al.* 1999) suggest that there may be a natural upper limit to steady state density of warm dust. If the dust density in a zodiacal cloud increases above a certain limit, then the controlling dynamical process switches from PR drag to mutual dust collisions. If the collision time scale is shorter than the PR drag time scale, then the dust will collide with itself at or close to its production site in the asteroid belt, and fragment into particles smaller than the blowout size. Thus, if a system's density is in the "collisional regime," the dust should extend from the source zone mostly outwards, whereas if a system is in the (lower density) "PR regime," the dust should extend from the source zone inwards. These calculations indicate that if the dust density in our asteroid belt went much over ~10 Zodi, the transport inward to the terrestrial zone would stop and grain fragments would be expelled from the solar system by direct radiation pressure. Of course, a large asteroid collision could bring the dust density in the belt temporarily above the steady-state level (Figure 5.1).

ZODIACAL DUST AROUND OTHER STARS

Cold Dust in the Kuiper Belts of Other Stars. The study of debris disks around main sequence stars began with the discovery of far-IR excess in the spectral energy distribution (SED) of α Lyr (Vega) early in the IRAS mission (Aumann *et al.* 1984; see Backman and Paresce 1993 for a review). Based on IRAS survey results, about 15% of nearby normal main sequence stars of all spectral types have circumstellar dust with characteristic temperature almost always less than 150 K. These dust envelopes may be connected to planetesimal belts resembling our Kuiper Belt. The IRAS detection limit around the nearest stars was $L_{\mathrm{dust}}/L_{*} > 10^{-5}$ where L_{dust} is the radiated luminosity of the dust and L_{*} is the stellar luminosity. The IRAS limit is about 100× the value for our zodiacal cloud and also 100× the theoretical upper limit on the amount of dust in our Kuiper Belt. Results from the ISO mission are still being calibrated (Becklin *et al.* 1999; Fajardo-Acosta *et al.* 1999) so that little is known yet about the incidence of lower density dust disks than IRAS measured over a decade ago.

At least some of the detected grains have estimated lifetimes shorter than even the youngest ages proposed for these systems. The short dust lifetimes lead to the very important conclusion that the detected grains are not primordial but must be resupplied from reservoirs consisting of larger bodies with longer lifetimes. Thus, it seems that these systems contain “planetesimal” (asteroid and comet) populations which are the sources of the dust, as is the case for our solar system’s zodiacal cloud. The dust around the solar-type star ε Eri has been imaged at submillimeter wavelengths (Greaves *et al.* 1998; Figure 5.4). The disk temperature and spatial scale of the emitting region is comparable to that expected in a Kuiper Belt, although with 1,000× more material than is thought to exist in our solar system.

Hot Dust and Inner Gaps. Stars with dust hotter than 150 K are rare, but our knowledge is limited by the searches carried out to date. The IRAS sensitivity (3σ at 25 μm) to a zodiacal cloud morphologically like ours, illuminated by a G2 primary star, would be roughly 500 Zodi. Only a handful of stars have dust at or above this level.

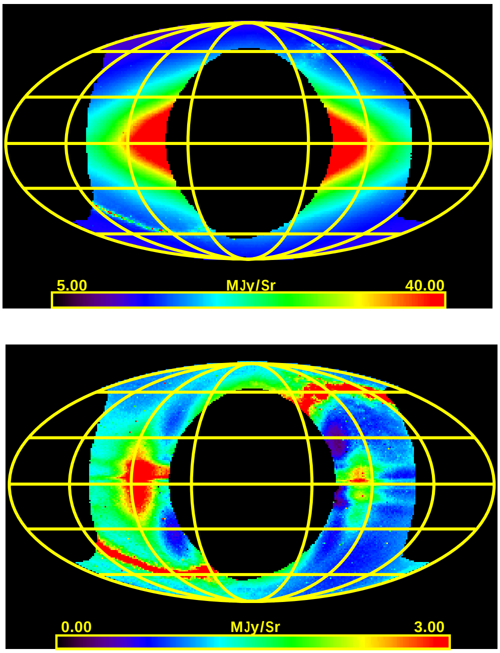

Figure 5.3a. COBE results for the 25 µm zodiacal emission (top) and with a smooth model removed from the data (bottom) to reveal concentrations of dust ahead and behind the Earth’s orbit (Reach et al. 1995).

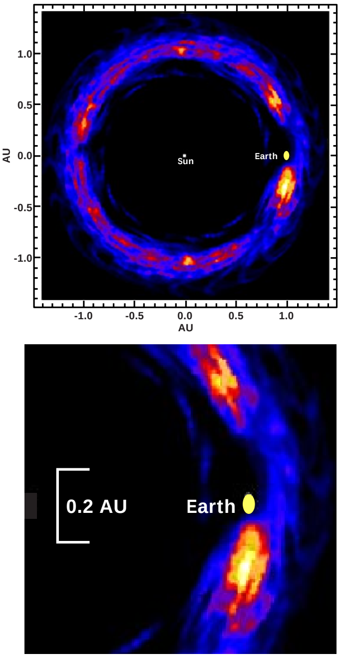

Figure 5.3b. A numerical simulation of dust in the solar system shows dust concentrated in a wake behind the Earth as seen from above the ecliptic plane (top) and in a magnified view (bottom) (Dermott et al. 1994).

The spectral energy distributions of the brightest IRAS systems imply transitions from outer, cool, high-density zones to inner, warm, low-density zones at temperatures of roughly 100, 70, 125, and 60 K for α Lyr, α PsA, β Pic, and ε Eri, respectively. These transitions may represent boundaries between regions containing many versus few planetesimals. The inner low-density zones therefore could be the regions in which planetesimals have mostly finished accumulating into planets (Nakano 1988).

To date, about eight main sequence stars have warm, detectable dust within the central "hole." The most prominent of these stars is β Pic with inferred temperatures up to at least 350 K (Fajardo-Acosta *et al.* 1993). The disk around β Pic shows a drop in density inward of a radius of about 40 AU (2 arcsec) in Hubble Space Telescope (HST) images (Burrows *et al.* 1995). The transition at 30 to 40 AU is intriguingly like the modeled result of "erosion" of the inner edge of the Kuiper Belt in our system due to planetary perturbations, especially by Neptune (Duncan *et al*. 1995). This influence removes the comet nuclei which would be parent bodies for dust in the same region. The finite thickness of the β Pic disk (Artymowicz *et al.* 1989; Kalas and Jewitt 1995) suggests that one or more planets at least 1000 km in diameter must be embedded in the disk to maintain the requisite dynamical heating.

Knacke *et al.* (1993) found clear signs in the inner few arcsec of the disk of 10 µm crystalline silicate emission with a spectrum resembling cometary dust but not interstellar or protostellar grains. Pantin *et al.* (1999) found evidence for crystalline silicates and water ice in the mid-IR spectrum in this object. These results are intriguing given the transient and usually red-shifted extra absorption features observed in some of the star's optical and UV lines. These have been interpreted as signs of infalling comets vaporizing along our line of sight to the star (e.g. Beust *et al.* 1996).

The range of ages for β Pic and the other main sequence stars with warm disks fall in the 10^7-10^8 yr time scale expected for the formation of planets (Wetherill 1991; Lissauer 1993), continuing into the long end-game of "heavy bombardment." These systems are certainly older than the 10^4 to 10^6 years needed for first-generation dust to condense in cooling protoplanetary disk nebulae and accrete into planetesimals. Some stars with ages estimated from Ca II, Li, or Stromgren indices to be older than 1 Gyr have far-IR excesses (Backman and Paresce 1993), evidence that planetesimal dust can persist well into the main sequence stage. It is interesting to note that 55 Cancri, with an age of > 3 billion years, has at least one Jupiter-mass planet as determined from radial velocity measurements, a faint disk imaged in the near-IR (Trilling and Brown 1998).

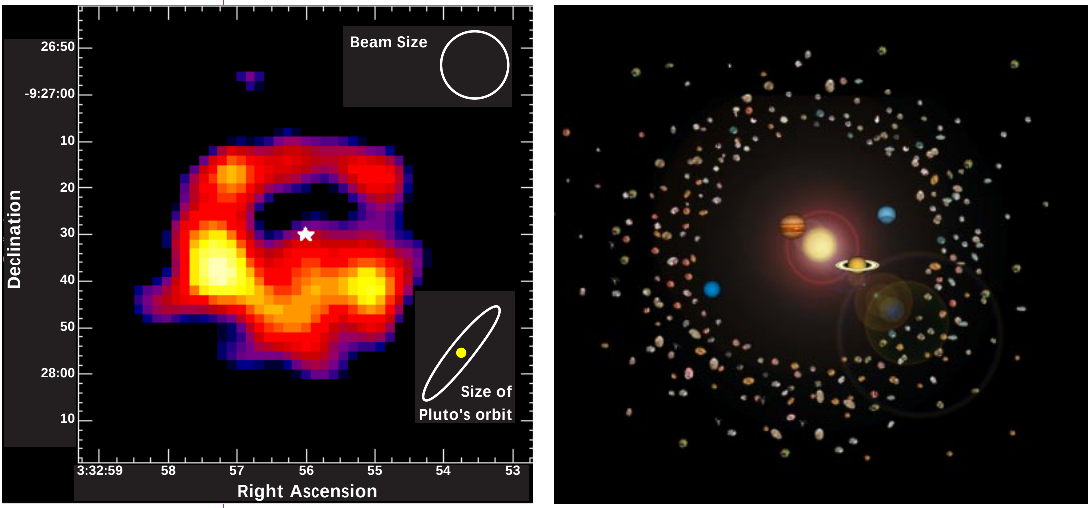

Figure 5.4. A sub-mm image (left) from the James Clerk Maxwell Telescope (JCMT) showing emission from the dust disk of the solar type star ε Eridani (Greaves et al. 1998). A face-on schematic view of our own solar system (right), including illustrative Kuiper Belt objects, as it would be seen at the distance of ε Eri, is shown for comparison.

PROSPECTS FOR IMPROVED KNOWLEDGE OF THE ZODIACAL CLOUDS

Far Infrared Observations. The zodiacal dust is most easily studied at infrared wavelengths because of the favorable contrast with the central star. While the ISO satellite made significant contributions to our understanding of the composition of the grains in the brightest disks, difficulties in calibrating the long wavelength data have so far precluded major advances in our knowledge of the dust content of disks much fainter than those first measured by IRAS. The Space Infrared Telescope Facility (SIRTF) will make dramatic advances in our knowledge of faint dust disks by using arrays of detectors at wavelengths from 25 to 160 μm to detect very low levels of dust emission. SIRTF will be able to measure fractional dust components as small as $L_{dust}/L_* = 10^{-6}$ and potentially approaching the solar system level of $\sim 10^{-7}$ for some stars (Werner *et al*. 1995). The dust observed in the far-infrared is typically colder than ~100 K and is located 10 to 50 AU from the central star, corresponding to the Kuiper Belt region of our solar system. To the extent that the outer solar system provides a reservoir of dust that slowly migrates inward, the SIRTF measurements will set a lower limit on the amount of dust that might be found in the inner solar system. SIRTF will also obtain spectral energy distributions of exo-zodiacal disks that can be inverted to yield models of the spatial distribution of dust well inside of SIRTF's diffraction limit. The 2.5 m telescope on the Stratospheric Observatory for Infrared Astronomy (SOFIA) and various ground-based submillimeter telescopes will provide higher spatial information relative to SIRTF for the brighter disks.

Interferometric Observations. Ground-based interferometers observing in the 10 μm atmospheric window will look for warm zodiacal dust around TPF candidate stars down to the level of 1-10 Zodi. Zodiacal emission will be detectable as an infrared excess after sup-

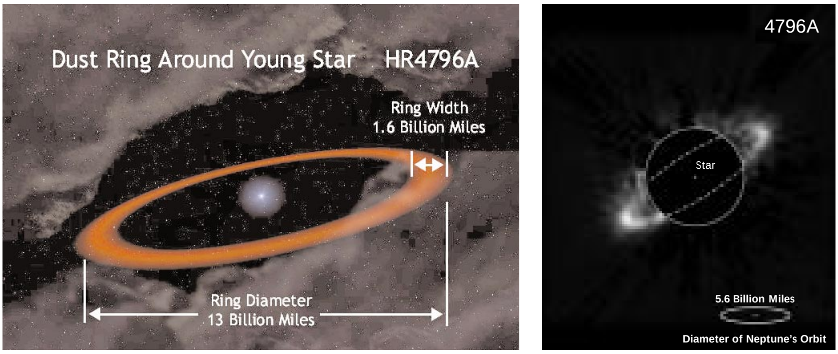

Figure 5.5. HST/NICMOS images of a dust disk around the star HR 4796A. Although the central part of the image is blocked by the glare of the central star, a prominent dust ring with a central gap is revealed by these observations (right). An artist's concept is shown on the left (courtesy of Smith, Schneider, and Becklin et al. 1999).

pression of the star by interferometric nulling (Angel 1997). Two U.S. ground-based projects have as an explicit goal the determination of exo-zodiacal emission in support of TPF: NASA's Keck Interferometer (operational in 2001) and the University of Arizona's Large Binocular Telescope (LBT; operational in 2004). Both interferometers nominally have the sensitivity to detect ~1 Zodi clouds, although their actual performance will depend on systematic effects that will have to be assessed as they become operational. The Keck and LBT interferometers will study the zodiacal clouds around nearby stars on different spatial scales due to their different (and fixed) interferometric baselines: 85 m for the Keck and 14.4 m for the LBT. The LBT will sample the habitable zone directly for stars at 10 pc, whereas Keck will measure regions closer to the star. The combination of the data from these instruments will constrain models for the distribution of dust in the inner regions of the target stars. Europe's Very Large Telescope-Interferometer (VLT-I) will be configured for mid-infrared imaging and may have a nulling capability when it comes online in 2003; this capability will be important for measuring TPF target stars in the southern hemisphere.

Other Techniques. Coronagraphic measurements from ground or space-based telescopes can determine the distribution of dust with ~1 arcsecond resolution in the brightest disks from visual and near-infrared observations (Figure 5.5; Becklin *et al*. 1999). The combination of information on the scattered and emitted radiation from dust will result in models that constrain many properties of the disks and the dust grains that comprise them. To date, the large contrast between light from the central star and the faint scattered light in the disks has restricted this study to the densest disks. Advanced coronagraphic instruments using adaptive optics could improve the detectable level of disk emission by 2 to 3 orders of magnitude and should be considered as a complement to the infrared techniques (Malbet, Yu, and Shao 1995; Angel, Cheng, and Woolf 1986; Trauger *et al*. 1998). The nulling experiment on the Space Interferometry Mission (SIM) may be able to push visible light measurements to within a few hundredths of an arcsecond of the central star in the brightest disks, corresponding to a few tenths of an AU for a star at 10 pc.

CONCLUSIONS

The zodiacal emission can, if sufficiently bright, hide terrestrial planets in other planetary systems. An important conclusion from the Exo-Zodiacal Dust Workshop (Backman *et al.* 1998) is that, based on the information presently available, there are no obvious correlations between the amount of warm or cold dust and stellar properties such as spectral type, multiplicity, presence of planetary companions, etc. There are only hints of correlations of dust quantity, particularly for hot inner material relevant to TPF searches, with age. This lack of correlation may reflect the accidents of nature (amount of material in the protoplanetary disk) and nurture (number and orbital distribution of planets) on the evolution of dust disks, as well as the paucity of stars for which we have the relevant data. We will improve our theoretical understanding as data on cold dust become available from SIRTF, SOFIA, and various submillimeter telescopes; on warm dust from ground-based imaging interferometers, coronagraphic measurements, and SIRTF spectroscopy; and on the presence of planets from astrometric and Doppler measurements. The combination of these data sets will lead to reliable predictions of the ability of TPF to detect planets toward individual stars before the start of the construction phase of TPF.

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