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DUSTY CIRCUMSTELLAR DISKS

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■ **Abstract** Dusty circumstellar disks in orbit around main-sequence stars were discovered in 1983 by the infrared astronomical satellite. It was the first time material that was not another star had been seen in orbit around a main-sequence star other than our Sun. Since that time, analyses of data from the infrared astronomical satellite, the infrared space observatory, and ground-based telescopes have enabled astronomers to paint a picture of dusty disks around numerous main-sequence and post–main-sequence stars. This review describes, primarily in an evolutionary framework, the properties of some dusty disks orbiting, first, pre–main-sequence stars, then main-sequence and post–main-sequence stars, and ending with white dwarfs.

1. INTRODUCTION

What are circumstellar (CS) disks and why should we care about them? Disks appear at many scales in astronomy—from spiral galaxies to rings around planets. In this article, our concern is with rings or disks that contain particulate material and that orbit stars at various stages in their life cycles. For main-sequence stars such as the Sun, the primary interest in such disks is that they could be related to the formation and/or existence of planets and smaller objects, such as comets and asteroids. After stars have evolved beyond the main sequence, orbiting disks are rare and often portend unusual, unexpected, and still unexplained phenomena.

The discovery of dusty CS disks around main-sequence stars was perhaps the most notable achievement of the infrared astronomical satellite (IRAS), which flew in 1983. IRAS, a joint venture of the United States, the Netherlands, and the United Kingdom, found that some bright nearby stars, including Vega and Fomalhaut, emit much more radiation at wavelengths between 25 and 100 μm than can be produced solely by the stellar photospheres. The spectral energy distribution of this excess infrared (IR) radiation is generally consistent with models wherein the emission arises from dust particles in CS disks whose characteristic radii are a few tens or hundreds of astronomical units. These grains absorb the optical and ultraviolet light from the central star and then radiate this energy away in the IR. Such stars have been dubbed "Vega-like."

At most stars, the particles emit most vigorously at wavelengths between 25 and 200 μm. Such wavelengths are difficult or impossible to study from the ground. Thus, in the years since IRAS flew, observational progress has been slow. Indeed, for approximately 15 years, except for one star (β Pictoris), no one was able to image the distribution of dust particles around the Vega-like stars.

Recently, there have been significant observational breakthroughs. From the ground, with sensitive detectors on large telescopes, images have been obtained of disks that orbit a few of the Vega-like stars (including Vega itself). These observations have been of thermal emission from grains at IR wavelengths between 10 and 25 μm, and, also, in the microwave band, near 1 mm wavelength. In addition, the NICMOS camera on the Hubble space telescope (HST) has imaged 1- to 2-μm radiation scattered by grains orbiting in disks and rings around a few stars.

Although most of the detected material in most of the disks consists of small particles, at a few stars modest amounts of gas have also been seen. The dust particles that comprise the disks are relevant to the formation of comets, asteroids, and planets, whereas the principal relevance of the gas is to the formation of giant gassy planets, such as Jupiter and Saturn.

The first portion of this article is structured along the lines of stellar evolution, beginning about 5–10 million years after the formation of a star, putting it in the last stages of the pre–main-sequence evolution. This is when massive disks that surround many stars have, by and large, dissipated and only relatively little gas and dust remain. The formation of larger bodies—"planetesimals" and planets—is either well along or is not going to happen. We next consider disks around main-sequence stars. These are either remnants of the star formation process or, more likely, debris from the destruction of larger objects, such as comets or asteroids. Evidence for the existence of dusty debris from ancient comets is seen in our own planetary system in the vicinity of the orbit of the Earth.

Finally, we consider stars in post–main-sequence stages of evolution—the red giants and white dwarfs. Surprisingly, a small percentage of such stars appears to be surrounded by orbiting dusty disks. The origins of most of these disks are mysteries whose eventual understanding will, no doubt, reveal interesting and important astronomical phenomena.

Following discussion of stellar and CS evolution, we consider some general properties of CS dust clouds, for example, their sizes and relationship to the Kuiper cometary region of our solar system, and how one may estimate cloud masses from measured fluxes at submillimeter wavelengths.

Considering the 16-year-long interest in the Vega-like stars, beginning with Aumann et al. (1984), it is remarkable that this article is the first review of the phenomenon to ever appear in this publication. Detailed discussions of β Pictoris, the most studied of all the Vega-like stars, have appeared in companion series (Artymowicz 1997, Vidal-Madjar et al. 1998). Other substantial reviews of dusty material around main-sequence stars are those by Backman and colleagues (Backman & Paresce 1993, Lagrange et al. 2000). The plan of the present review is to focus on topics not emphasized in previous reviews.

One might look on this review as a summary tribute to the monumental contribution of IRAS to this field, a contribution still going on. If the promise of SIRTF and SOFIA are realized, then our knowledge of dusty CS material should soon expand into important new realms. For myself, this represents a bit of deja vu; my article on mass loss from red giant stars (Zuckerman 1980) appeared shortly before the launch of IRAS, which revolutionized our knowledge of that field.

2. THE EVOLUTION OF STARS AND THEIR CIRCUMSTELLAR DISKS

2.1. Pre–Main-Sequence Evolution

When intermediate-mass stars form, they are often surrounded by massive disks of dust and gas that astronomers can detect via strong IR dust emission and radio emission from carbon monoxide molecules. After a few million years, the small particles in the disk that are responsible for the IR emission begin to disappear, either because they clump together or because they are lost from the system. The timescale for loss of small particles can be determined by measuring the amount of material as a function of the age of the young stars. Generally stellar ages can be determined most reliably for stars that are members of a cluster.

The best measure of the mass of small particles comes from submillimeter continuum fluxes (see Section 4.1). A less precise and more limited, but easier to obtain, measure of dust abundance is the "optical depth," tau, of a dusty disk: $\tau = L_{IR}/L_*$. Here L_{IR} is the total excess energy emitted in the IR and L_* is the bolometric luminosity of the underlying star. Tau represents the optical depth of an orbiting dust disk to ultraviolet and visual radiation. After absorbing these radiations, the dust particles reradiate the energy in the (far) IR.

We want to know how long it takes for the dust particles to disappear because this constrains the time it takes to form planetesimals, i.e., bodies that look like present-day comets and asteroids. We want to know how long it takes the gas to dissipate because this will give an upper limit to the time available to form gas giant planets. A recent discussion of these and related issues pertaining to pre–main-sequence stars can be found elsewhere (Mannings et al. 2000).

Young stars were initially discovered to lie in or near dusty, interstellar molecular clouds. These stars are usually less than a few million years old, often less than one million years old. These are the T Tauri stars of approximately one solar mass or less (Mathieu 1994, Bodenheimer 1995, Hartmann & Kenyon 1996, Feigelson & Montmerle 1999) and the Herbig Ae stars, which are a few times more massive than the Sun and which will evolve into A-type main-sequence stars like Vega and Fomalhaut (Waelkens & Waters 1998).

It has not been easy to find old T Tauri stars, in the 10- to 20-million-year range, because such stars are hard to identify with IR and optical techniques. Recently, surveys of X-ray emission, especially with the German ROSAT satellite, have enabled detection of many stars that appear to be old or post T Tauri stars (e.g., Neuhäuser 1997). Such stars have been discovered because they emit many more X-rays than do older, main-sequence, stars.

Not only did ROSAT enable detection of oldish T Tauri stars in regions surrounding various dusty molecular clouds, it also led to the clear recognition (Kastner et al. 1997) of the nearest known region of recent star formation, the TW Hydrae Association, named in honor of its first known member, the classical T Tauri star, TW Hya. Combination of ROSAT data, lithium abundances from optical spectra, and distance determinations with the Hipparcos satellite, indicate that the TW Hya Association (hereafter TWA) is about 10 million years old and only $\sim$60 pc from Earth (Webb et al. 1999). The primary reason this close T Tauri Association went unrecognized for so long is that the massive molecular cloud from which the Association stars formed has dissipated; the only clouds that remain in the vicinity are those that orbit the stars, i.e., CS disks.

Because of their proximity to Earth, dust around stars in the TWA can be studied with special clarity. One of the most interesting Association members is an A-type star, HR 4796. Initially, IRAS discovered that about 0.5% of the total energy from HR 4796 is emitted at IR wavelengths—HR 4796 is the dustiest A-type star in the *Bright Star Catalog* (Jura 1991). By comparison, other relatively dusty A-type stars, such as Vega and Fomalhaut (discussed below), emit a 100 times smaller percentage of their total energy at IR wavelengths.

The 10- to 20-μm thermal emission from dust heated by HR 4796 was imaged at telescopes in Hawaii and Chile (Jayawardhana et al. 1998, Koerner et al. 1998, Telesco et al. 2000). At about the same time, an image of a narrow ring of dust particles that scatter light at a wavelength of 1.1 μm was obtained with the NICMOS camera on the HST (Figure 1, lefthand panel). Two very different classes of models have been proposed to explain this remarkable structure.

The narrow containment of the ring particles and the abrupt inner and outer truncation of the ring around this relatively young star suggests dynamical constraints imposed by one or more related, but as yet unseen, bodies. The question of how such bodies, presumably planets or planetary embryos, could have formed so quickly at such large distances from the star presents an interesting challange to those who model planet formation (Kenyon et al. 1999). In the case of HR 4796, the dynamical situation is complicated by the gravitational field of a nearby M-type companion star (Wyatt et al. 1999). No planet mass objects are required in the alternative class of models where the ring structure is generated by dust particles migrating in an optically thin gaseous disk (T. Takeuchi & P. Artymowicz, submitted for publication). Under the influence of radiation pressure from the central star, dust grains of different sizes segregate according to orbital semi-major axis. Smaller grains can be concentrated into a ring in the outer region of the gas disk. However, no gas has yet been seen near HR 4796 (Greaves

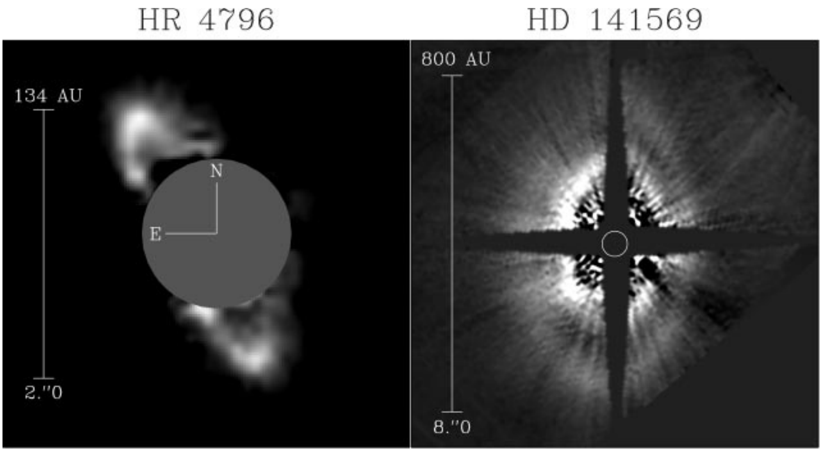

Figure 1 Images obtained at a wavelength of 1.1 μm with the NICMOS infrared camera on the Hubble space telescope in 1998. (*Left*) HR 4796, a star about 10 million years old located 67 pc from Earth. The region near the star is unusable and is masked out. The diameter of the surrounding inclined dust ring, which reflects starlight toward Earth, is about 150 AU (Schneider et al. 1999). Recently, the ring was imaged (with improved spatial resolution) at optical wavelengths with the STIS camera on the Hubble Space Telescope (Schneider 2001). (*Right*) HD 141569, a star about 100 pc from Earth whose age is probably under 10 million years. The diameter of the inclined dusty disk is about 700 AU, and there is an indication of a gap between the brightly reflecting dust close to the star and the fainter dust further out. Gaseous carbon monoxide molecules detected in orbit around HD 141569 with a radio telescope seem to be confined primarily to the region interior to the gap. (From Weinberger et al. 1999.)

et al. 2000b). If gas-dust disks can generate axisymmetric structures such as are seen at HR 4796 and HD 141569 (Figure 1 and below), then convincing planet detection via imaging of dust should include specific non-axisymmetric structure. Non-axisymmetric structure is seen at submillimeter wavelengths at a few main-sequence stars (see discussion in Section 2.2.1).

Another A-type star imaged by NICMOS is HD 141569, (Figure 1, *right*) (Weinberger et al. 1999, 2000, Augereau et al. 1999a). HD 141569, ~100 pc from Earth, is the closest Ae-type star. This star is not a member of the TWA, but it was chosen for NICMOS imaging because it has a lot of surrounding dust—about 1% of its energy is emitted at IR wavelengths—and surrounding molecular gas. The mass contained in hydrogen molecules orbiting HD 141569 is deduced to be on the order of tens of Earth masses, based on a distance of 100 pc [rather than the 200 pc assumed by Zuckerman et al. (1995a)]. HD 141569 is quite young; from placement of its two M-type companions on pre–main-sequence tracks, Weinberger et al. (2000) estimate a system age of ~5 Myr. A-type stars like HR 4796 and HD 141569 appear to be on the zero-age main sequence (see discussion in Section 2.2.1), unlike their late-type companions which are definitely pre-main sequence.

A potentially exciting aspect of the NICMOS/HST image is the apparent gap ~250 astronomical units from HD 141569 between inner and outer dusty regions. Such a gap would be anticipated if a substantial planet were forming there. The companion M-type stars a few disk diameters away could also influence the dynamics of the dusty disk (Weinberger et al. 2000). However, as for HR 4796 above, the gap and other axisymmetric dust structures may be generated by the combined action of gas drag and radiation pressure (T. Takeuchi & P. Artymowicz, submitted for publication). Requisite gas has already been detected at HD 141569 (Zuckerman et al. 1995a). As at HR 4796A, thermal IR emission at 10- and 18-μm wavelength is detected from the inner ~100 AU of the HD 141569 disk (Fisher et al. 2000b), well inside the region of the gap.

As with HD141569 and HR 4796, most dwarf stars detected in the far-IR by IRAS and not associated with interstellar molecular clouds are A-type, for the following reasons. The far-IR luminosity of a Vega-like star as seen from Earth is due to a combination of (*a*) the proximity of the star, (*b*) its bolometric luminosity, and (*c*) the mass and radial distribution of small particles in its dusty CS disk. As described in Section 2.2.3, as stars age, on average the mass of orbiting dust declines quickly. Only a few stars less luminous than A-stars are both sufficiently young and close to Earth that their far-IR luminosities exceeded the IRAS detectability threshold.

The most dramatic of these IR-bright, low-luminosity, stars are found in the TWA, specifically HD 98800 (K5), Hen3-600 (M2), and TW Hydrae itself (K7). At each star the dust optical depth, tau, is approximately 0.1 (Zuckerman & Becklin 1993a, Zuckerman et al. 1995a), an order of magnitude larger than the already very high taus of HR 4796 and HD 141569.

Various authors have argued that most dust particles detected at most Vega-like stars are "second generation." That is, they are generated by the breaking down of larger objects (e.g., comets) rather than direct remnants of the star formation process (Backman & Paresce 1993, Zuckerman & Becklin 1993b, Lagrange et al. 2000). The optical depth tau is so large at HD 98800, TW Hydrae, and Hen3-600 and these stars are sufficiently young that the observed dust may be mostly primordial rather than second generational.

A choice between primordial and second-generational might be facilitated by comparing the composition of dust particles surrounding TWA members with dust composition near young T Tauri stars and in solar system comets. Sitko et al. (2000) obtained 3–13 μm spectra of HD 98800, HR 4796, and TW Hydrae itself. These spectra and those of T Tauri stars and comets are sufficiently non-uniform that no sweeping generalizations regarding dust composition can be drawn at this time. The spectrum of TW Hya lacks the 11.2 μm emission feature characteristic of crystalline olivine seen in some young stars and some long-period comets. By concentrating on the distribution of particle sizes (rather than their composition), one may also distinguish between primordial and second-generational dust. For example, Prato et al. (2001) note that the micron size grains responsible for the 10 μm silicate feature at HD 98800 have Poynting-Robertson lifetimes much less than the age of the star; thus such grains must be second generational.

Although TW Hydrae is apparently a single star, HD 98800 is a quartet of stars and Hen3-600 a triplet (Torres et al. 1995, Webb et al. 1999, Muzerolle et al. 2000, R.A. Webb, I.N. Reid & B. Zuckerman, submitted for publication). Thus, large dust optical depth is not confined to any particular stellar multiplicity. In the HD 98800 system, the dust seen by IRAS is orbiting the optical secondary "B" (Gehrz et al. 1999, Low et al. 1999, Koerner et al. 2000, Prato et al. 2001), which is a double-lined spectroscopic binary (Torres et al. 1995). Its spectrum can be fit quite well all the way from the mid-IR through the submillimeter with a single blackbody of temperature, $\sim$160 K (Low et al. 1999, Koerner et al. 2000, Prato et al. 2001). Nonetheless, because it is generally understood that, independent of composition and particle size, the emissivity of plausible grain constituents is smaller at wavelengths near 1 mm than at 60–100 μm (e.g., Pollack et al. 1994), it is not possible to fit spectra like that of HD 98800 with single temperature grains. That is, the flux at 1 mm should always fall below a blackbody extrapolation of emission from the warm grains that account for the IRAS fluxes (e. g. Zuckerman & Becklin 1993b, Jura et al. 1998). When it does not, then cool grains must also be present.

Especially striking evidence for the presence of cool grains not detected by IRAS is seen at Hen3-600 (Figure 2). Here the warm dust detected in the far-IR by IRAS orbits the optical primary (Jayawardhana et al. 1999a), which is a spectroscopic binary. But, as seen in Figure 2, at submillimeter wavelengths, there is excess emission above that emitted by the warm dust. That is, both Hen3-600 and HD 98800 are orbited by approximately an Earth mass of dust too cold to have been detected by IRAS. A plausible, but still unproven, distribution of the dust at these systems is depicted in Figure 3.

A discussion of the distribution and IR detectability of disk particles as a function of stellar luminosity is presented in Section 4.2. There we note that the luminosity of A-type stars is sufficiently great to heat most surrounding dust particles so that they are warm enough to be detected in the far-IR. This, clearly, is not the case at the much less luminous, late-type stars HD 98800 and Hen3-600, and at the K2 star ε Eri discussed in Section 2.2.1. Thus, 850-μm emission was detected from TWA 7, an M1-type star not detected in the far-IR by IRAS (R.A. Webb, B. Zuckerman, J.S. Greaves & W.S. Holland, submitted for publication). TWA 7 is ringed by a substantial quantity of cold ($\sim$20 K) grains located $\sim$100 AU from the star. Substantially hotter dust closer to the star is apparently much less abundant. At this moment, we know of no Vega-like star other than TWA 7 that has been detected either in the mid-IR or at submillimeter wavelengths that was not first shown by IRAS or the Infrared Space Observatory (ISO) to have associated excess far-IR emission.

Of the stars in the TWA, the one with by far the largest mass of orbiting dust particles is TW Hya (R.A. Webb, B. Zuckerman, J.S. Greaves & W.S. Holland,

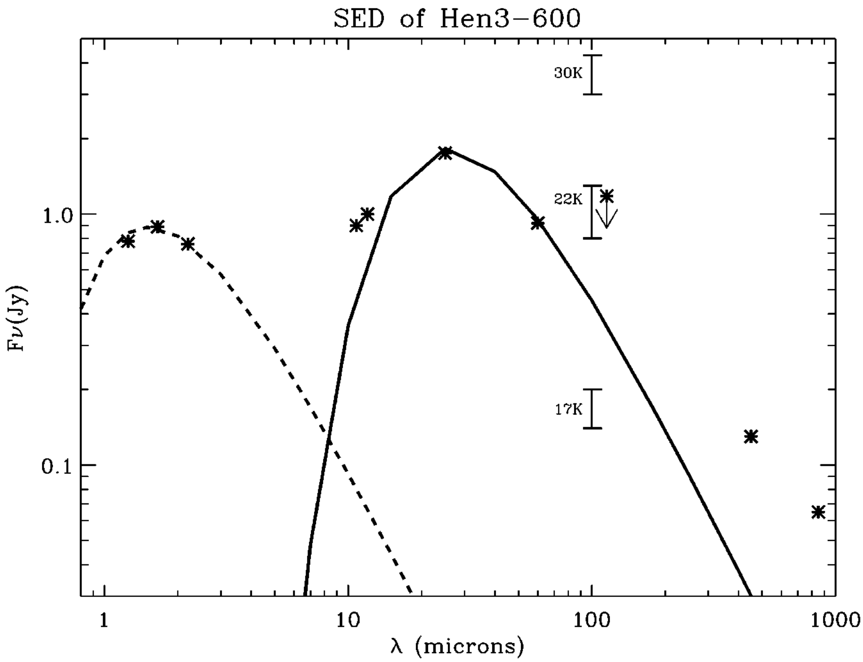

Figure 2 The spectral energy distribution (SED) of Hen 3-600. (*Dashed line*) The stellar photosphere, a 3350 K blackbody; (*solid line*) a 200 K blackbody fitted to the IRAS 25- and 60-μm data points. The IRAS 100-μm upper limit has been offset slightly to longer wavelengths for clarity. The 450- and 850-μm fluxes measured with SCUBA on the James Clerk Maxwell telescope at the Mauna Kea Observatory lie well above the emission anticipated from the 200 K grains—much cooler grains must also be present. (*Vertical bars*) The 100-μm flux that would be emitted by plausible dust grains at the labeled temperatures, extrapolated from the 850-μm flux. Dust responsible for the measured 850-μm flux but much hotter than $\sim$20 K would generate 60- and 100-μm flux in excess of that measured by IRAS. (From Webb 2000, R.A. Webb, B. Zuckerman, J.S. Greaves & W.S. Holland, submitted for publication.)

submitted for publication). In many respects it resembles classical T Tauri stars of substantially younger age (Rucinski & Krautter 1983). But because of its proximity to Earth (56 pc), the dusty material can be imaged with special clarity. HST images of light scattered at optical (Krist et al. 2000) and near-IR wavelengths (A.J. Weinberger, E.E. Becklin, G. Schneider, M. Silverstone, D. Hines, et al. submitted for publication) indicate the presence of a nearly face-on disk with a radius of at least 200 AU. At much longer wavelengths, near 7 mm, Wilner et al. (2000) imaged the disk with the very large array (VLA) and also found it to be extended, with a radius of $>$50 AU. Both the HST and VLA images have resolutions on the order of 0.1 arcsec, or about 5 AU at TW Hya. These images show no fine

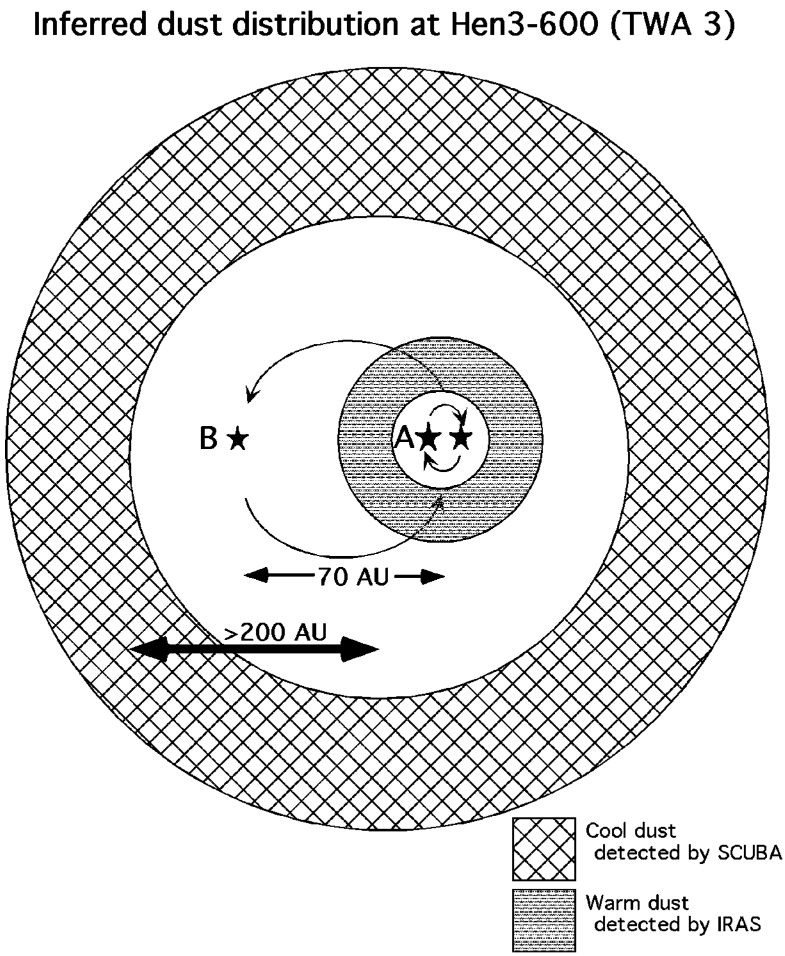

Figure 3 The dust distribution at Hen3-600 inferred from the spectral energy distribution shown in Figure 2. Sizes of the various regions not to scale. IRAS and mid-infrared cameras are primarily detecting the warm dust around the spectroscopic-binary primary. SCUBA reveals the cool dust which, likely, orbits the visual binary (AB). Based on large submillimeter fluxes, a similar picture is inferred for HD 98800. (From Webb 2000, R.A. Webb, B. Zuckerman, J.S. Greaves & W.S. Holland, submitted for publication.)

scale structure in the dust distribution such as is seen at HD 141569 and HR 4796.

Because of its proximity and its massive surrounding disk, the brightest molecular emission seen at a star of age ~10 million years is from TW Hya (Figure 4). Future observations of these molecules (and others yet to be detected) with sensitive interferometers that operate at millimeter wavelengths promise to help us to better understand the chemical conditions in a potential protoplanetary disk. The interferometers could reveal changes in chemistry as a function of distance from TW Hya. Such chemical data may be helpful to planetary scientists who try to understand the chemistry of our own forming planetary system 10 million years after the formation of the Sun. Chemistry in disks that surround other T Tauri stars will be studied with future interferometers, but TW Hya should remain unique: It is the closest known classical T Tauri star, and thus fine details can be resolved in its CS disk, and it is the oldest known T Tauri star that still retains substantial quantities of surrounding molecular gas. Kastner et al. (1999) suggest that the substantial X-ray luminosity of young stars such as TW Hya may regulate accretion and chemistry of disk material. Indeed, Weintraub et al. (2000) regard the strong X-ray flux from TW Hya as the most likely cause of excitation of observed near-IR emission from H_2 molecules located in the inner portion of the disk.

The current mass of molecular gas at TW Hya has been estimated with two different techniques but remains uncertain. One technique is millimeter wavelength observation of CO rotational emission. If the CO/H_2 ratio in TW Hya's disk is comparable to that found in interstellar molecular clouds, then the dust and gas masses at TW Hya are comparable (Kastner et al. 1997). That is, compared with interstellar abundances, the gas is depleted by a factor of ~100 relative to the small dust particles. The quantity of remaining gas, ~10 Earth masses, is insufficient to form planets similar to Jupiter. However, CO freeze-out onto grains or photodissociation might result in a CO/H_2 ratio smaller than interstellar; then the CO technique could underestimate the mass of hydrogen gas.

An independent estimate of gas mass may be obtained from measurement of accretion rates of disk material onto TW Hya. Muzerolle et al. (2000) modeled the H α and ultraviolet continuum emission from TW Hya and concluded that the mass accretion rate is about one order of magnitude smaller than at typical (younger) T Tauri stars. This suggests a gas mass depleted (relative to interstellar) by a factor of ~10, or about 10 times more gas than was estimated by Kastner et al. (1997). While the Kastner technique might underestimate the total gas content in the disk, the Muzerolle et al. model may lead to an overestimate of gas mass for the following reasons. First, they note that accretion rate estimates from H α are uncertain by a factor of 5. Second, the excess ultraviolet luminosity at TW Hya may be due in part or entirely to an active chromosphere (White & Ghez 2001) rather than accretion. And, third, the spectra of Sitko et al. (2000) indicate modest excess continuum flux between 2 and 8 μm wavelength. This suggests that warm gas accreting onto TW Hya may not be accompanied by much dust or, alternatively, that the accretion rates are actually quite small. Finally, the Muzerolle and Kastner

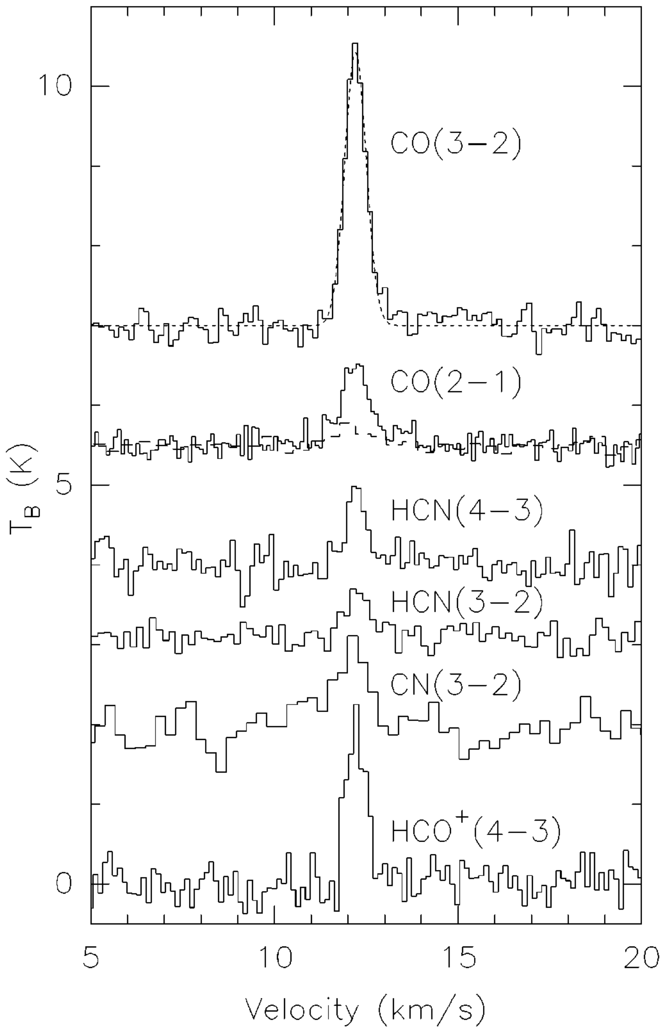

Figure 4 Molecular spectra observed toward TW Hya with the James Clerk Maxwell telescope (Kastner et al. 1997). (*Abscissa*) Heliocentric radial velocity; (*ordinate*) the relative main beam brightness temperature (T_B). The two spectra labeled CO(2-1) are of the ^{12}CO (*solid curve*) and ^{13}CO (*dashed curve*) isotopomers (the ^{13}CO spectrum has been expanded along the ordinate by a factor of two). The *short dashed curve* overlaying the CO(3-2) profile represents the best-fit Gaussian function.

masses need not agree precisely because the former. were probing the innermost portions of the disk, whereas the latter were more sensitive to the outer regions.

The amount of gas near the other (10 Myr old) stars in the TWA is very small. CO has not been detected at any (Zuckerman et al. 1995a). Other than TW Hya, the only one of 11 stars observed by Muzerolle et al. (2000) that showed any evidence of accretion is Hen3-600A, where the rate is about 10 times less than at TW Hya.

Eta Chamaeleontis is a recently discovered, compact, nearby cluster (97 pc from Earth) whose age is comparable to that of the TWA (Mamajek et al. 1999, 2000). A few of its stars were sufficiently dusty to have been detected by IRAS. But they are substantially less dusty than the dustiest stars in the TWA, which is a much more diffuse cluster. Although deducing general patterns from a sample of only two clusters is probably unwarranted, a comparison suggests that dusty disks might dissipate more quickly in crowded star-forming regions.

2.2. The Main Sequence

2.2.1. INDIVIDUAL VEGA-LIKE STARS Closer to Earth than the TW Hya Association is the best studied of all Vega-like stars—β Pictoris (β Pic), a naked-eye star located in the southern hemisphere. In the context of the formation and existence of planetary systems, proper interpretation of the various phenomena seen at β Pic and other main-sequence stars depends on reasonably accurate knowledge of stellar age. The Vega-like star HD 207129 is a dramatic example of how uncertain the age of a field star can be; age estimates in the literature for HD 207129 differ by 4.5 Byrs (see Section 2.2.3 for additional details).

For many years the age of β Pic was in dispute, with estimates in the literature ranging from ~10 to >100 Myrs. But now the preponderance of evidence indicates that β Pic is quite young, probably ~15 Myrs old. The first argument was presented by Jura et al. (1993), who noted that except for HR 4796, β Pic has the largest tau of any A-type star in the *Bright Star Catalog*; large tau usually indicates a young star (Section 2.2.3). Subsequently, Jura et al. (1998) showed that β Pic lies on the A-star zero-age main sequence along with HR 4796, HD 141569, and several other obviously very young stars (Figure 5) (see Section 2.2.3 for additional discussion of the A-star HR diagram). Then Barrado y Navascues et al. (1999) found that β Pic and the M-type stars GL 799 and GL 803 appear to be moving through space together. Thus, they probably formed together.

Most recently, the young stars HIP 23309 (MO) and HIP 29964 (K6) were also found to have the same space motion as β Pic (Song et al. 2001b). Of the four late-type co-moving companions, HIP 23309 is the closest to β Pic, at a separation of about 8 pc. At an average distance from Earth of only ~20 pc, β Pic and its four companions appear to comprise the nearest group of kinematically related very young stars.

The estimated age of these four stars is 15 +/− 5 million years, based on their location on theoretical pre-main sequence tracks on the Hertzsprung-Russell diagram. Among dwarf M-type stars not classified as T Tauri stars, GL 803 is the only one known to display excess 60-μm emission in the IRAS *Faint Source Catalog* (I. Song et al. submitted for publication). As the amount of dust around stars seems to decline as the stars age (Section 2.2.3), the far-IR detectability of GL 803 is no doubt due to its unusually small product of age and distance from Earth (10 pc).

A primary interest in young, nearby stars is their unique suitability for detection of cooling, Jupiter-mass planets via adaptive optics (AO) imaging. One may define an “AO detectability index” (AODI) as the product of stellar age and distance from Earth; the smaller the AODI, the better suited a star is for AO imaging of planets. Along with binary star GL 799, GL 803 has the smallest known AODI. Thus, GL 803 has already been carefully examined for cooling planets with the AO system on the Keck telescope (B. Macintosh et al. manuscript in preparation).

The disk around β Pic was imaged at a wavelength of 9000 A with a camera with coronagraphic optics (Smith & Terrile 1984) within a year after IRAS discovered the large excess IR emission. The image revealed that Earth lies very nearly in the plane of the β Pic disk, which extends hundreds of astronomical units from the star in a northeast-southwest direction. A recent image (Figure 6) reveals scattered light out to $\sim$1800 AU along the northeast side of the disk. The initial coronagraphic studies and many subsequent ones in the optical and IR from the ground and with the HST have revealed many fascinating aspects of the β Pic environment. Various recent major reviews have focused entirely (Artymowicz 1997, Vidar-Madjar et al. 1998) or substantially (Lagrange et al. 2000) on β Pic. Therefore, to limit this review to material that has not been extensively discussed elsewhere, the following paragraphs present only a brief outline of a few β Pic “highlights.” The reader is referred to the above three reviews for many more β Pic details.

There is a diminution of dust density within a few tens of astronomical units from β Pic compared with the dust abundance farther out on the disk (Lagage & Pantin 1994). This might be due to planet formation, but it could also be due to dust destruction or ejection. Optical spectra of ionized calcium lines show time-variable components. These have been interpreted as due to comet-like objects falling onto β Pic, sometimes as many as a few per week (Beust et al. 1998 and references therein). Modest masses of carbon monoxide (CO) molecules and neutral carbon atoms have been detected in the ultraviolet spectrum of β Pic with HST (Roberge et al. 2000). It is suggested that these gaseous species result from evaporation of comet-like bodies out to $\sim$100 AU from β Pic.

Precise optical images were interpreted initially as showing a warp in the disk within $\sim$80 AU of β Pic. However, recent coronagraphic images obtained with the space telescope imaging spectrograph suggest that the apparent warp may rather be the superposition of two disk-like components inclined with respect to each other by $\sim$5 degrees (Heap et al. 2000). Such a structure might be produced by the gravitational influence of a giant planet in orbit $\sim$20 AU from β Pic.

Substantially more distant from β Pic, optical and submillimeter images point toward potentially remarkable phenomena. Reanalysis of and comparison among ground-based and HST images has revealed fine structure in the northeast arm of the disk (Kalas et al. 2000). The disk, which appeared more uniform in earlier, less ambitious image reductions, may be composed of numerous concentric rings. How such structure, 500–800 AU from β Pic, is generated and maintained is unclear; Kalas et al. (2001a) investigate the possibility of a recent, close encounter with a passing star.

Kalas et al. (2000) were unable to discern any similar structure at comparable distances from β Pic in the southwest arm. However, images obtained at a wavelength of 850 μm with the SCUBA camera on the James Clerk Maxwell telescope (JCMT) at Mauna Kea Observatory show the unexpected presence of an emission peak offset from β Pic $\sim$34″ (650 AU) to the southwest (Figure 7*b*). It is not known whether this emission is associated with the star or whether it is a totally unrelated background galaxy located near the edge of the observable Universe. Arguments favoring a physical association with the star include (*a*) location of the offset peak close to the plane of the inner disk and (*b*) the relatively high 850-μm brightness of the offset peak—very few distant submillimeter galaxies radiate as brightly (19 mJy) as does the offset peak. Based on the measured surface density, $\sim$20/square degree, of 20-mJy, 850-μm galaxies, we estimate a probability of $\sim 10^{-3}$ that Holland et al. (1998) would have seen one so close to the disk plane of one of the three stars they investigated with SCUBA.

Thus, if the 850-μm emission is associated with β Pic, then the fine structure seen by Kalas et al. (2000) is at comparable distance, but on the opposite side of the star. The submillimeter emission must be due to warm dust grains because companion stars and planets would radiate too faintly at 850 μm to be detected from Earth. The dust cannot be associated with a companion star because such a star would easily be seen in the IR. Perhaps there is a brown dwarf or giant planet embedded in the dusty disk and generating structure (Liou & Zook 1999, Ozernoy et al. 2000).

Moving to older stars, 850-μm images of three are displayed in Figure 7. Vega (α Lyr) and Fomalhaut (α PsA) are nearby A-type stars, whereas ε Eri (K-type) is even nearer but with a mass slightly less than that of our Sun. These stars were choosen for submillimeter imaging because they are among the strongest of the excess far-IR emitters detected by IRAS. The images seen in Figure 7 are the first ever of the dust distribution around these three stars. The easiest to interpret is Fomalhaut, which is consistent with a ring of material located approximately 80 AU from the star. As in the case of β Pic, we view Fomalhaut more or less in the plane of its dusty disk. The dust at ε Eri also is distributed in a ring-like fashion, but here the view is face on; that is, the dust orbits the star at a distance of about 50 AU and nearly in the plane of the sky.

An obvious interpretation of the dust rings at ε Eri and at Fomalhaut is that we are seeing analogs of the Kuiper Belt of comets that orbits the Sun just outside of the orbits of Pluto and Neptune. In the case of ε Eri and Fomalhaut, we do not see actual comets but rather dust particles that are produced by the (partial) destruction of comets, probably many more than exist in the Kuiper Belt. Given that the ages of ε Eri and Fomalhaut are estimated to be 730 and 200 million years, respectively (Song et al. 2000, Barrado y Navascues et al. 1997), we may speculate that the structures are similar to what our own Kuiper Belt must have been like billions of years ago.

The regions of relatively low 850-μm emission inside of the dust rings at ε Eri and Fomalhaut might be caused by the formation of planets. In the case of Fomalhaut and other A-type stars, another conceivable explanation for a central cavity could be sublimation of icy dust particles during the lifetime of the disk. But such an explanation does not explain the relatively low dust abundance near ε Eri because the star is insufficiently luminous to vaporize icy grains over such an extended region.

The JCMT image of ε Eri contains a surprising feature—a peak of emission in the ring to the east and slightly south of the star. If this is a real nonuniformity in the ring structure, then it is not easily explained. Given the large mass of dust implied by the submillimeter fluxes, a mighty "cosmic collision" would have had to have occurred if shattering of a massive object were involved. A more plausible explanation of such structure is the presence of one or more planets that gravitationally scatter and trap dust particles in mean motion resonances (Liou & Zook 1999, Ozernoy et al. 2000).

Finally, Vega presents yet another mystery. As is seen in Figure 7*c* the peak 850-μm emission seems to lie off to one side of the star. As at β Pic, it is conceivable, albeit unlikely, that the emission peak is due to a distant background galaxy. But if the peak in 850-μm emission is due to dust in orbit around Vega, then, as at ε Eri and β Pic, we do not understand the cause of the emission. In particular, it seems unlikely that dust could be retained in orbit around a substellar companion for so long, Vega being probably a few hundred million years old (Barrado y Navascues 1998). Perhaps the 850-μm peak is associated with a planet orbiting in the dust disk (Ozernoy et al. 2000).

2.2.2. GAS AT THE VEGA-LIKE STARS Sensitive millimeter searches have revealed molecular gas at the young stars TW Hya and HD 141569 mentioned in Section 2.1. But such studies of the Vega-like stars have been mostly fruitless. One success was detection of CO from the dusty A-type star 49 Cet (Zuckerman et al. 1995a), indicating two Earth masses of H_2 molecules. 49 Cet has a large tau, is located near the A-star ZAMS (Jura et al. 1998), and is undoubtedly very young. In spite of deep searches, radio astronomers have been unable to detect CO and some other diatomic molecules in the vicinity of β Pic, HR 4796, ε Eri, and Fomalhaut (Liseau & Artymowicz 1998, Liseau 1999, Greaves et al. 2000b and references therein). Coulson et al. (1998) searched for CO at some dusty stars that, typically, are much farther away and/or younger than stars considered in this review.

The reliability of deriving total CS gas (H_2) mass from CO mass has been questioned because, relative to H_2, CO might be preferentially removed from the gas phase by certain processes. Recently, Thi et al. (2001) claimed that at three young stars this is precisely what has occurred. Thus, quoting from their January 4, 2001 *Nature* abstract: “The debris disks that encircle more than 15% of nearby main-sequence stars appear to have very small amounts of gas based on observations of the tracer molecule CO. Here we report [ISO] observations of the lowest rotational transitions of H_2 that reveal large amounts of gas in the debris disks around the stars β Pic, 49 Cet, and HD 135344. The gas masses calculated from the data are several hundreds to a 1000 times greater than those estimated from the CO observations and yield gas/dust ratios of the same order as the interstellar value.”

Only four days later (on January 8), Lecavelier des Etangs et al. (2000) reported Far Ultraviolet Spectroscopic Explorer (FUSE) spectra of H_2 toward β Pic that appear to contradict, by orders of magnitude, the H_2 mass calculated by Thi et al. from the ISO spectra. Specifically, the FUSE spectra fail to reveal H_2 absorption of observed OVI line emission. Given the edge-on aspect of the β Pic debris disk, if the OVI emission is coming from the star, then the circumstellar CO/H_2 abundance ratio is likely to be greater, not less, than interstellar. (This can be understood if the CO observed in the UV with HST is coming from comets and very little H_2 remains from the primordial protoplanetary nebula.)

Comparison of intensity and linewidths indicate that OVI and CIII emission lines seen toward β Pic originate at the star and not in the diffuse interstellar medium (Shelton et al. 2000, M. Deleuil, J.-C. Bouret, A. Lecavelier des Etangs, A. Roberge, A. Vidal-Madjar et al. submitted for publication; M. Jura, A. Roberge, and R. Shelton, personal communication). If so, then the ultraviolet spectra are consistent with the CO results, to wit, very little gas is present in the dusty CS disk around β Pic. Perhaps future FUSE spectra will clarify the situation at other Vega-like stars.

Optical detection of narrow, variable Ca II and Na I absorption lines in A-type shell stars has been more fruitful. Welsh et al. (1998) argue that the infalling, evaporating comet model developed for β Pic by Beust and colleagues is applicable also for HR 10 (A2IV) and HD 85905 (A2V). References to earlier optical observations of similar stars by Carol Grady and others can be found in Welsh et al. (1998) and Lagrange et al. (2000).

2.2.3. EVOLUTION OF DUST ABUNDANCES WITH TIME Vega and Fomalhaut, with probable ages of hundreds of millions of years (Barrado y Navascues 1998), are less dusty than HR 4796 and β Pic, whose ages are ten to tens of millions of years. More generally, far IR observations of main-sequence stars in nearby young clusters and in the field indicate that as stars age, on average, less and less dust is retained in their vicinity (Figure 8) (Habing et al. 1999, 2001, Spangler et al. 2001). Loss mechanisms include radiation pressure, Poynting-Robertson drag, collisions, and sublimation (e.g., Backman & Paresce 1993, Wyatt et al. 1999). Clearing times are sufficiently short that the preponderance of the micron-size particles seen in CS disks around all but the very youngest main-sequence stars likely is the product of

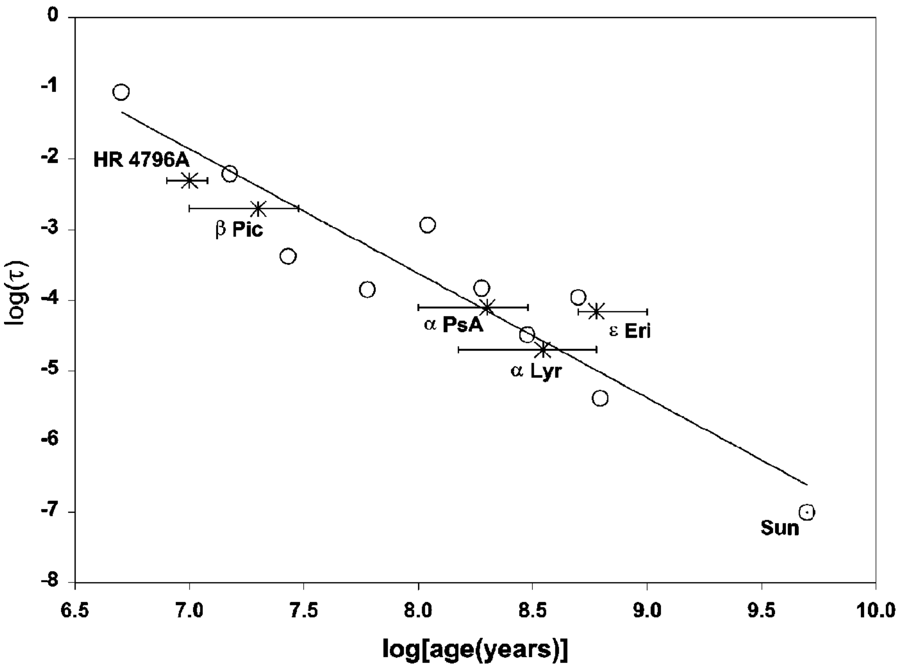

Figure 8 Vega-like stars and the Sun are plotted along with *circles*, which represent nearby clusters, including α Per, the Pleiades, Ursa Major, Coma Ber, and the Hyades (Spangler et al. 2001). For field stars the indicated Vega-type stars represent a rough upper-envelope of tau at a given age. The value of tau for the Sun is based on Zodiacal dust within 5 AU of the Sun and does not include a contribution to tau from dust in the Kuiper Belt (which is unlikely to be much greater than the tau attributed to the Zodiacal dust). (*Line*) A regression fit to the data with slope −1.75.

destruction of asteroids and comets, much as the dust component of the zodiacal light seen in the inner parts of our solar system is a remnant of similar debris.

Estimation of the total mass of small particles that orbit a given Vega-like star is relatively straightforward (Section 4). Nonetheless, because IRAS and ISO were sufficiently sensitive to detect only the brighter dust disks, many evolutionary questions remain. For example, does dust abundance diminish with time in similar fashion for massive and low-mass stars? How do abundances vary with time in binary star systems as a function of primary and secondary separation? Or the same question, but for the situation where the secondary is a massive planet rather than a star? SIRTF will surely reveal many new examples of the Vega phenomenon at low-luminosity stars and, for small tau, for the more massive (A-type) stars.

Placement of these anticipated new data in an evolutionary sequence will also require reliable techniques for measuring stellar age for field stars not in clusters. Various groups have attempted to estimate ages of field, Vega-like stars (Dunkin et al.

1997, Barrado y Navascues 1998, Barrado y Navascues et al. 1999, Lachaume et al. 1999, Zuckerman & Webb 2000, Silverstone 2000, Song et al. 2001a), with varying degrees of success. Clues to age include kinematics, theoretical evolutionary tracks, stellar activity, and lithium abundances, but these are not always mutually consistent. For example, based on the weakness of Ca II, K-line emission, Jourdain de Muizon et al. (1999) deduce that the dusty G-type star HD 207129 is older than the Sun; they also model the likely structure and 4.6 billion year history of the system. This star stands out in their sample (Habing et al. 1999) as being unusually dusty for its (old) age. But relying on space motions and location in space, Zuckerman & Webb (2000) estimate the age of HD 207129 to be only $\sim$40 million years. If correct, this young age makes the presence of a substantial dusty disk easy to understand.

Jura et al. (1998) have developed a successful technique for determining ages of some A-type stars. Using Hipparcos parallaxes, they constructed a color-magnitude diagram for A-type stars in the *Bright Star Catalog* (Figure 5). A-type stars with pre–main-sequence late-type companions whose ages can be deduced from evolutionary tracks delineate the lower envelope of the diagram; this nicely characterizes the zero-age main sequence for A-type stars. Lowrance et al. (2000) extended Jura's analysis of the *Bright Star Catalog* by adding A-type stars in the Hyades, Praesepe, IC2391, α Per, and the Pleiades (Figure 5). These stars lie in generally well-defined regions on the diagram, consistent with the known ages of these clusters (as determined by other techniques). Dust abundance versus age for stars in these clusters is shown in Figure 8 and discussed by Spangler et al. (2001).

2.2.4. VEGA-LIKE STARS ORBITED BY PLANETS With the discovery that $\sim$5% of solar-like stars are orbited by "hot-Jupiters" (e.g., Marcy & Butler 2000), an obvious question arose: Can we deduce a relationship between these "planet stars" and the Vega phenomenon? Because most known Vega-like stars are A-type and planet stars are of later type, at this early stage the overlap between these two classes of objects must be small. Indeed it consists of just one star, ε Eri (K2). A weak signal, due to a roughly Jupiter-mass planet, appears to be present in radial velocity measurements, extending over the past 20 years, and obtained by a number of groups (Hatzes et al. 2000). This planet orbits with a semimajor axis of 3.4 AU, well inside of the dusty disk, semimajor axis of $\sim$50 AU, imaged in the submillimeter (Figure 7*d*), whose apparently clumpy structure has been attributed to the gravity of a planet (Liou & Zook 1999, Ozernoy et al. 2000). This outer planet is hypothesized to orbit well outside the 3.4 AU orbit of the radial velocity–discovered planet.

Papers have appeared claiming detection of dust at planet star 55 Cnc via thermal far-IR (Dominik et al. 1998), and submillimeter emission (Jayawardhana et al. 2000), and via images of scattered near-IR light (Trilling & Brown 1998). Similar claims have been made for the presence of extended near-IR emission due to scattering from dust at planet stars ρ CrB and HD 210277 (Trilling et al. 2000).

However, in actuality, none of these "detections" appear to be of dust at the stars in question. At 55 Cnc, the submillimeter flux initially attributed to dust orbiting the star, is reported instead to be from nearby background sources (Greaves et al. 2000a). Then, most likely, the reported excess far-IR is from the same background sources rather than from the star. With the NICMOS near-IR coronagraph on the HST, Schneider et al. (2001) failed to see any evidence of dust near 55 Cnc at a level several times fainter than that reported from ground-based images (Trilling & Brown 1998).

Only a tiny handful of Vega-like stars—those having very large tau, such as β Pic—have ever been detected in scattered light at near-IR or optical wavelengths in extensive deep surveys (Smith et al. 1992, Kalas & Jewitt 1996). Nondetections include the most prominent far-IR and submillimeter dust disks, for example Vega, Fomalhaut, and ε Eri (Kalas & Jewitt 1996). Planet stars 55 Cnc, ρCrB, and HD 210277 have never been detected in the far-IR. This is to be expected given their likely old age ($\gtrsim$5 Gyrs, G. Marcy, personal communication) and the decline in CS dust abundance as indicated in Figure 8. Thus, the chance that they will be orbited by dust in sufficient quantities to be detectable in the near-IR with a current ground-based coronagraphic system is virtually nil in the opinion of this reviewer.

2.3. First-Ascent Giant Stars

The particulate matter in CS disks around main-sequence stars may be envisioned as a natural consequence of the star formation process—leftover material that was not incorporated into large objects, or alternatively, particles generated by (partial) destruction of the large objects. In either case, by the time an intermediate-mass star evolves off the main sequence, one expects little dust to remain. Thus, the discovery by IRAS of large amounts of dust near a small but not insignificant percentage of ordinary first-ascent G and K giant stars of luminosity class III came as quite a surprise (Zuckerman et al. 1995b, Plets et al. 1997). Because of IRAS's mediocre spatial resolution at far-IR wavelengths, there was a remote possibility that many of the associations between star and far-IR source were bogus and that the far-IR emission was instead associated with background galaxies. Observations at 60 and 90 μm with a 3 $\times$ 3 pixel camera on ISO show conclusively that a strong majority of the far-IR sources are truly associated with the stars (Kim et al. 2001).

HD 233517 (K2), perhaps the most striking example of a luminosity class III giant star with excess far-IR emission, was initially interpreted to be a Vega-like main-sequence star with a disk that is spatially resolved at 10-μm wavelength (Skinner et al. 1995). However, its large radial velocity (Zuckerman et al. 1995a) was an initial clue that HD 233517 is not a main-sequence star. Subsequent spectroscopy confirmed that HD 233517 is a dusty luminosity class III red giant (Fekel et al. 1996), and subsequent imaging with spatial resolution superior to that of Skinner et al. failed to resolve the 10-μm emission region (Fisher et al. 2000a). The photospheric lithium abundance is $\sim$10 times larger than in meteorites, thus indicating lithium production inside of HD 233517 (Balachandran et al. 2000). A similarly dusty star, HD 219025, was initially suggested to be young and on the main sequence (Whitelock et al. 1995). But the Hipparcos measured distance to HD 219025 and arguments given in Fekel et al. (1996) indicate its giant nature beyond any doubt.

Initially it appeared that there might be a connection between the presence of far-IR excess emission and lithium richness in first-ascent giant stars (e.g., de la Reza et al. 1997 and references therein). But recent surveys for lithium in giants with IR excesses show no such correlation (Fekel & Watson 1998, Jasniewicz et al. 1999).

At first glance, one might interpret the dusty giant stars as simply a long-lived tail of the main-sequence Vega phenomenon. But because of the large taus at many of the giant stars (Zuckerman et al. 1995b) and the decrease of tau with age on the main sequence, such an explanation seems unlikely. Thus, three other models have been proposed (Jura 1999 and references therein) to explain the presence of substantial dust near luminosity class III giant stars: (*a*) destruction of comets and particulate matter in a Kuiper Belt–like region as the central star increases its luminosity as it leaves the main sequence; (*b*) mass ejection; and (*c*) stellar heating of dust in random interstellar clouds that, by chance, lie near some G and K giants. Jura discussed problems with all three models and concluded with a preference for the first model. His analysis indicated that the relative size of the far-IR emitting regions would be very different in the three cases. In particular, the size of the emission region in the second model would be an order of magnitude larger than in the first, whereas the third model size would be yet another order of magnitude larger.

ISO measurements indicate that, spatially, the emission at 11 stars is extended with respect to the ISO point-spread function (Kim et al. 2001). A Kuiper Belt–like region (first model) would appear spatially unresolved in the ISO detectors. Thus, a simple picture of small dust particles orbiting $\sim$100 AU from the giant stars is ruled out by the ISO images. Unfortunately, these images do not clearly distinguish between the second and third models. If mass outflow is involved, then there is the additional question of where the outflow starts—at the star or farther out, for example in the Kuiper Belt region?

Kalas et al. (2001b) used an optical coronagraph to show that six main-sequence stars classified as Vega-like are, in actuality, heating interstellar dust that happens to lie in their vicinity; the R-band images reveal reflection nebulosity that is almost certainly attributable to interstellar rather than CS dust particles. The stars in question all lie 150 pc or more from Earth. Within $\sim$60 pc of Earth there is a low-density "bubble" that contains very little interstellar dust (Sfeir et al. 1999), but this is not the case at greater distances. Thus, for moderately distant main-sequence and first-ascent giant stars, the choice between interstellar and CS dust is not easy. Most luminosity class III giant stars with known far-IR excess are located beyond the local bubble.

Neither the second nor third model can be readily reconciled with all existing data (Jura 1999). In addition, gas has never been detected at any of these dusty systems. At this moment, we do not understand the origin and nature of the dust near G and K giant stars. Perhaps optical coronagraphy and/or far-IR images from SOFIA and SIRTF can resolve the mystery.

2.4. Asymptotic and Postasymptotic Giant Branch Stars

IRAS detected strong mid- and far-IR emission from numerous, luminous AGB stars with either carbon-rich or oxygen-rich photospheres. In most cases, the IR emission is produced by dust grains entrained in outflowing winds, i.e., not in a CS disk. But a few of these IR-bright, evolved stars have been found to possess peculiar characteristics of various sorts. For example, a handful of stars with carbon-rich photospheres heat nearby associated silicate dust grains that formed in an oxygen-rich environment. When measured at such stars, CO rotational lines are typically only 1–2 km s^{-1} wide and much narrower than lines characteristic of outflowing winds (e.g., Bujarrabal et al. 1988). That is, the narrow line widths indicate velocities characteristic of orbital motion of gas many hundreds of astronomical units from the stars, rather than gas escaping from the stellar surface (Jura & Kahane 1999).

A plausible, but not yet proven, model for most of these stars with unusual IR and/or CO spectra is the following. The primary, giant star is a member of a binary system. When the primary ejects large amounts of mass while it is on the asymptotic giant branch, the gravitational field of the secondary deflects some of this outflowing material into a circumbinary disk that is gravitationally bound to the two stars. An example may be found in Jura et al. (2000), who present a moderately detailed picture of AC Her. The companion star necessary in such a scenario has already been detected near some, but not all, of the unusual giant stars (e.g., Waters et al. 1993, van Winckel et al. 1998). At least a few of the disks show evidence for large-scale clumpiness, the nature of which is not now understood.

2.5. White Dwarfs

A dusty CS disk in orbit around a white dwarf could be detected as excess IR emission. At this moment, in spite of searches at hundreds of white dwarfs, we know of only one, G29-38, that is surrounded by dust grains—these emit strongly at wavelengths between 2 and 20 μm (Tokunaga et al. 1990, Chary et al. 1999). The origin and survival of the dust is a mystery. Perhaps G29-38 is embedded in a moderately dense interstellar cloud and dust from the cloud has been gravitationally drawn into a disk orbiting the star. Or perhaps there has been some kind of cosmic catastrophe near G29-38, say a collision of two moderately massive objects that has partially shattered them. Or perhaps G29-38 is pulling material off of a nearby but unseen companion. Or perhaps the answer is one of any number of other exotic hypotheses. In any event, the presence of an unusually large abundance of heavy elements in the photosphere of G29-38 indicates that the dust particles are being accreted onto the star (Koester et al. 1997, Chary et al. 1999, Zuckerman & Reid 1998). This is consistent with the short orbital lifetimes expected under the influence of the Poynting-Robertson effect (Tokunaga et al. 1990).

3. GENERAL SURVEYS FOR CIRCUMSTELLAR DUST

Witteborn et al. (1982) carried out an unsuccessful, but prescient, ground-based, pre-IRAS, mid-IR search for “fragmentation debris near Ursa Major Stream stars.” All major subsequent surveys have employed the IRAS or ISO satellites. Early surveys are considered in Backman & Paresce (1993) and some of the more recent ones in Lagrange et al. (2000). Remarkably, as can be seen from the discussion below, 16 years after announcement of the Vega phenomenon by Aumann et al. (1984), new Vega-like and dusty post–main-sequence stars are still to be mined from the IRAS database.

Early survey efforts matched stellar catalogs against the IRAS *Point Source Catalog* (see Backman & Paresce 1993). More recent searches for spatial correlations rely on the more sensitive IRAS *Faint Source Catalog* (FSC), which, however, includes stars only 10 degrees or more from the Galactic plane. One recent such survey is due to Mannings & Barlow (1998), who correlated the FSC against the *Michigan Spectral Catalog* (e.g., Houk & Smith-Moore 1988). Of the 73 stars listed in Mannings & Barlow (1998) as newly identified candidate main-sequence stars with debris disks, $\sim$20 are B-type. In this review, I have shied away from B-type stars because of the possibility that IR emission may be generated by free-free processes rather than by dust particles. At about half of the listed non–B-type stars, the IR excess is present only at 25 μm (such stars were not detected by IRAS at either 60 or 100 μm). The reality of this sample, and of similar 25-μm excess stars listed in Mannings & Barlow (1998), would imply the existence of a substantial number of stars with warm but little or no cool dust. Thus, it would be worthwhile to verify or deny the 25-μm excesses with a ground-based camera. Even without such ground-based data, Sylvester & Mannings (2000) found, from a careful comparison of optical and IRAS positions, that in some cases the IRAS source is not physically associated with the star listed by Mannings & Barlow (1998). Similarly, with ISO, Silverstone (2000) found that toward many stars apparently associated IRAS 60 μm sources were, in reality, IR cirrus.

Silverstone (2000) correlated the IRAS FSC with stars in the *Michigan Spectral Catalog* (south of –12 degrees declination) and with the Smithsonian Astrophysical Observatory (SAO) catalog for stars north of –12 degrees. His list of excess stars satisfied the following criteria: (*a*) IRAS-detected 60-μm flux, (*b*) Hipparcos parallax, and (*c*) spectral type in the range B9 to K. He also included a luminosity cutoff to exclude giant stars. Silverstone’s final list of probable 60-μm excess stars in the FSC numbered close to 200. Within the constraints of Silverstone’s source selection criteria and the sky coverage of the FSC, his work likely represents the most comprehensive search to date of the IRAS catalogs for Vega-like stars.

Silverstone's primary goal was to use the C100 3 × 3 array camera of ISOPHOT to detect excess 60- and/or 90-μm emission from F- and G-type stars that were either marginally detected or not detected by IRAS at 60 μm. His ISOPHOT targets of stars not detected by IRAS comprised two samples, one that was volume limited and another composed of stars likely to be young. His conclusions for the decline of tau at young F- and G-type field stars are generally consistent with cluster results and are included as one (unlabeled) point in Figure 8.

Decin et al. (2000) also used the C100 3 × 3 ISOPHOT array to search for excess 60-μm emission toward 30 G-type dwarfs, five of which displayed an excess. A similar, albeit smaller, set of such stars has been identified with the ISOPHOT photometer on ISO (Fajardo-Acosta et al. 1999). Filters at 3.6, 11.5, and 20.0 μm revealed a few stars with apparent 20-μm excesses but none with 11.5-μm excess. In another program, Fajardo-Acosta et al. (2000) cross-correlated the 2 Micron All-Sky Survey (2MASS) and IRAS catalogs and found a handful of stars with apparent 12-μm excess emission. A decade ago, Aumann & Probst (1991) found that only a tiny fraction of stars with apparent 12-μm IRAS excesses, when observed from the ground through a small aperture, are truly associated with the excess. Thus, as Fajardo-Acosta et al. recognize, the stars they have identified should be observed with a ground-based camera.

Such observations have begun with a mid-IR camera on the Keck I telescope; two of the Fajardo-Acosta stars were observed at 11.5 and 17.9 μm, but excess emission was not seen (I. Song et al. submitted for publication). These Keck observations were part of a larger program to check for excess IR emission at $\sim$500 nearby M-type dwarf stars. Correlation of the IRAS FSC and Hipparcos positions yielded three M-type stars with apparent 25 μm flux excesses and one M-type star (GL 803) with a 60 μm excess. But Keck camera data showed that none of these 25 μm excesses are real. Thus, none of the $\sim$500 stars have excess 25 μm flux, at the level to which IRAS was sensitive.

As noted in Section 2.3, Kalas et al. (2001b) have shown that some of the more distant stars classified by others as Vega-like are, in fact, not surrounded by CS disks. Rather, the far-IR emission detected by IRAS is generated by interstellar grains heated by the stars. The same is no doubt true of the 60-μm emission from some of the luminosity class III stars detected by IRAS.

Some previous papers and reviews have quoted the percentage of stars that display the Vega phenomenon. We suspect that such attempts are premature, in part because of problems and limitations of the sort mentioned above. There are additional difficulties. For example, detection of a 25- or 60-μm excess by IRAS depended on a star's distance from Earth, spectral type, and tau. For stars later than A-type, IRAS was able to detect excess emission only from stars with very large tau and rather close to Earth. How large should tau be for a star to qualify as Vega-like? Does the Sun—with tau $\sim 10^{-7}$ for dust interior to the giant planets, and with tau for dust in the Kuiper Belt region still uncertain but unlikely to be much larger than 10^{-7}—qualify? Hopefully, volume-limited surveys by SIRTF will provide some definite percentages.

4. PROPERTIES OF THE CIRCUMSTELLAR DUST

Astronomers have expended substantial effort to understand the radiation characteristics of small dust particles. Early work was on grains in interstellar clouds—such particles typically have submicron dimensions (Hildebrand 1983 and references therein). Observed CS disks have higher densities than do interstellar clouds and larger particles are present, either from the sticking together of small particles or from destruction of larger bodies. Perhaps the most interesting astrophysical aspects of the CS dust at a given star are its total mass and spatial distribution. Images such as Figure 7 give a large-scale picture but because the dust is heated by the central star, the dust visibility depends on its temperature as well as its spatial location. For example, the sharp cutoff in 850-μm emission outside of the bright "blobs" seen to the north and south of Fomalhaut is due in part to diminishing dust temperature as well as dust density.

Various researchers have developed models to match the IR spectral energy distributions of the Vega-like disks (e.g., Sylvester & Skinner 1996, Augereau et al. 1999b, Harvey & Jefferys 2000). Model parameters include the temperature and luminosity of the central star, the spatial distribution of the dust, the particle size distribution, the optical properties of the grains, and the disk mass. In the conventional modeling method, a wide grid of plausible parameters is established, and χ squared is minimized to find the maximum-likelihood model that best matches the spectral energy distribution (Augereau et al. 1999b, Sylvester & Skinner 1996). Harvey & Jefferys (2000) employed Bayesian techniques to model the dust cloud around Fomalhaut. They fitted far-IR and submillimeter data from the Kuiper Airborne Observatory, IRAS, and the JCMT. An advantage their technique has over more conventional ones is presentation of probability histograms for the model parameters; these clearly display how the likelihood of a model varies as the value of a parameter is changed.

4.1. Disk Mass

At a given distance from a star, the temperature of a dust particle depends on its size relative to the wavelength of the peak of its thermal IR emission. If the particle is small with respect to the wavelength of its peak IR emission, then such a particle will radiate inefficiently and its temperature will rise above the temperature a large particle would have at the same location. Near this peak of emission, for large and small particles alike, the amount of emission depends sensitively on the dust temperature because of the exponential in the denominator of the Planck function.

Thus, the appearance of the dust emission at a given wavelength results from a convolution of dust mass and temperature. To derive dust mass, it is best to use submillimeter data because (*a*) being on the Rayleigh-Jeans portion of the Planck curve, intensity is only linearly proportional to dust temperature; (*b*) optical depths being small, all the dust mass is perceived; (*c*) cold dust ($T < 20$ K) is readily detectable; and (*d*) for particles with radii smaller than the wavelength of observation, the dust mass is proportional to the submillimeter flux and only weakly dependent on particle size (Hildebrand 1983, Figure 2*b* in Pollack et al. 1994).

Particles that are much larger than the wavelength under investigation have relatively low surface-to-volume ratio and the opacity per gram of material diminishes. Therefore, for measurements at, say, one millimeter wavelength, dust "grains" larger than about 1 cm in size contribute little to the emission compared with smaller particles, even if most of the mass is in the larger ones.

Hence, submillimeter fluxes can provide only lower bounds to mass in orbit around stars—such observations will not reveal the presence of large objects such as comets, asteroids and planets, at least not directly. The existence of such bodies can be deduced indirectly if it can be shown that the detected dust results from breakdown of larger objects. This is likely the case at stars as old as Vega and Fomalhaut. For younger stars, such as β Pic or the pre–main-sequence stars discussed in Section 2.1, detected dust may be either left over from the star formation process or debris from the breakdown of larger objects, or some combination of the two.

As an illustrative example, consider the submillimeter flux (F_ν) measured at Earth that is emitted by an optically thin cloud or disk a distance R away.

$$F_\nu = \pi B_\nu \cdot 4\pi a^2 \cdot Q_\nu n_{\mathrm{gr}} V/4\pi R^2. \tag{1}$$

Here, πB_ν is the surface emittance of a single grain per unit area, $4\pi a^2$ is the emitting area of a grain of radius a, n_{gr} is the number of grains per unit volume, and V is the total volume of the cloud. Q_ν is the efficiency with which the grains absorb and emit waves of frequency ν. The total mass (M) of dust in the disk may be written

$$M = \rho N 4\pi a^3/3, \tag{2}$$

where N is the total number of grains in the cloud, and ρ is the density of a typical grain. Combining Equations 1 and 2 yields

$$M = F_\nu R^2/B_\nu k_\nu. \tag{3}$$

At submillimeter wavelengths, where $h\nu \ll kT$, the Planck function, B, can be written simply as $2kT/\lambda^2$. Thus, the calculated grain mass is not sensitively dependent on the grain temperature (which is often not well determined).

In Equation 3, k_ν is the opacity, that is, the absorption cross section per gram of material at frequency ν. For typical grain materials, the absorption cross section can be much smaller than the total extinction cross section—that is, the grains often have large albedos at wavelengths near a millimeter (Pollack et al. 1994). The opacity may be written as

$$k_\nu = (\pi a^2 Q_\nu)/(4\pi a^3 \rho/3) = 3Q_\nu/4a\rho. \tag{4}$$

This is the absorption per unit mass of dust, whose units are usually given in the literature as square centimeters per gram. Sometimes the opacity quoted in the literature is the absorption per unit mass of dust and gas combined. To obtain this from submillimeter dust emission (which is the measured quantity) requires an assumption about the ratio of the mass contained in gas to that contained in the dust particles; this ratio is often taken to be 100, the value typical of the interstellar medium. However, in CS disks, the gas-to-dust ratio is often much smaller than 100, and it is usually uncertain or unknown, so it is better to quote opacities in terms of dust mass only.

For some time, the value of k_ν at wavelengths near 1 mm was uncertain by at least an order of magnitude, resulting in corresponding uncertainty in dust masses (e.g., Hildebrand 1983). Recent laboratory and theoretical efforts have improved the situation so that now k_ν is probably known to a factor of 3 or so (Pollack et al. 1994, Agladze et al. 1996, Beckwith et al. 2000). In any event, one cannot obtain total masses contained in CS disks because objects of dimensions much larger than a few centimeters are effectively invisible even if they carry most of the mass of the disk.

That said, submillimeter fluxes from stars such as β Pictoris and HR 4796 that are just arriving on the main sequence indicate total dust masses about 20 times the mass of our Moon. The most common particle sizes range between 10 μm and a few millimeters. For older stars, such as Vega and Fomalhaut, total dust masses are 10 times less (e.g., Holland et al. 1998).

4.2. Disk Dimensions

In the far-IR, where the Vega-like stars are most prominent, neither IRAS nor ISO possessed adequate spatial resolution to map the emission in a satisfactory manner (e.g., Heinrichsen et al. 1998). This situation will change dramatically with the advent of SOFIA, but for the time being we must make do with images at optical, near-IR, and submillimeter wavelengths. Some of these images are discussed and shown in this review. In this subsection, I briefly summarize what they have revealed.

Given that an A-type star has more mass and gravity than one of K- or M-type, one might anticipate A-type stars to have larger dusty disks. If this is indeed true, then it is not yet apparent from existing images. Rather typical disk radii appear to be a few hundred astronomical units more or less independent of spectral type. For example, based on crude submillimeter maps of the A-type stars Vega, Fomalhaut, and β Pic, Zuckerman & Becklin (1993b) deduced that there was not much dust far from the stars that was too cold to have been detected by IRAS. This was clearly confirmed by the much better maps presented by Holland et al. (1998) (Figure 7) and the analysis of Fomalhaut by Harvey & Jefferys (2000). In contrast, submillimeter studies of late-type stars, such as ε Eri and those in the TW Hya Association, indicate (Figures 2, 3, 7*d*) that most of the dust mass is too cold to have been detected by IRAS. The luminosity of such stars is inadequate to heat grains with orbital semimajor axes $\sim>$100 AU to temperatures greater than the

$\sim$30 K required to generate substantial far-IR flux. Similarly, although ground-based mid-IR images reveal warm inner disk structure (e.g., Lagage & Pantin 1994), they don't characterize full disk sizes.

At β Pic, for which the best images currently exist, some dust is seen in scattered optical light out to $\sim$1000 AU (Figure 6), but most of the disk mass resides much closer to the star. At TW Hya, HST images of scattered light (Krist et al. 2000, A.J. Weinberger, E.E. Becklin, G. Schneider, M. Silverston, D. Hines, et al. submitted for publication) reveal dust out to a few hundred astronomical units, at which point due to diminished surface densities, or geometrical effects, or both, the (face-on) disk becomes indistinguishable from the background. Maps are not yet available of the other late-type, pre–main-sequence stars in the TW Hya Association, and the outer dimensions of the disks are generally ill-defined from analysis of the submillimeter spectrum (R.A. Webb, B. Zuckerman, J.S. Greaves & W.S. Holland, submitted for publication).

Thus, at most stars studied to date, the dust distribution appears similar to the likely distribution of material in the Kuiper Belt of our solar system, with a relatively sharp inner edge and a trailing off of density as one moves outward beyond 100 AU.

4.3. Particle Size Distribution

As noted by Krivov et al. (2000), "the size distribution of particles in a dust disk is determined by, and holds the key to sources, sinks, and dynamics of grains . . . The size distributions are not easy to retrieve, however." Krivov et al. (2000) solve for the size distribution of the dust particles in the β Pic disk with a "collision dominated" model in which grain collisional lifetimes are much shorter than their Poynting-Robertson lifetimes. (The opposite is true for zodiacal dust particles in the inner solar system of the Sun.)

A particle size distribution can be deduced from broadband and narrowband disk spectra and polarization. Most Vega-like disk particles are much larger than the submicron sizes that characterize interstellar dust. Particles with radii on the order of hundreds of microns or more are indicated by large submillimeter fluxes (Zuckerman & Becklin 1993b, Sylvester & Skinner 1996, R.A. Webb, B. Zuckerman, J.S. Greaves & W.S. Holland, submitted for publication). Usually only the youngest Vega-like stars display excess 10-μm emission (e.g., Aumann & Probst 1991, Jayawardhana et al. 1999b). A 10-μm silicate emission feature, when clearly present, implies the existence of (sub)micron size particles. A discussion of the 10-μm spectra of early type main-sequence stars, references to earlier studies, and comparison with terrestrial materials may be found in Fajardo-Acosta et al. (1998). At near-IR wavelengths, a neutral color of scattered light indicates the presence of micron-sized particles (e.g., at HR 4796, Schneider et al. 1999).

Grain temperatures may be estimated from the wavelength of peak emission. Grains with small albedos and diameters comparable to or larger than this wavelength will behave essentially like blackbodies located a distance from the central star appropriate to their temperature. The grains at Fomalhaut are one such example (Holland et al. 1998). Grains much smaller than the wavelength of their peak thermal emission will radiate less efficiently than blackbodies and, thus, when compared with black bodies will be hotter at a given distance from the central star. This is true for some of the grains at β Pic (Gillett 1986). Thus, measurement of the temperature of the dust as a function of location in a disk will indicate whether the radiating particles are large or small (e.g., see appendices in Sopka et al. 1985).

Another method for estimating grain sizes is from the spatial and wavelength dependence of polarized light. Voshchinnikov & Krugel (1999) and Krivova et al. (2000) model imaging optical polarimetry of the CS disk of β Pic obtained previously by other astronomers. Voshchinniov & Krugel assumed a strict power law grain size distribution, whereas Krivova et al. obtained a more detailed fit to the observations by assuming a cutoff to the power law below a few microns, arguing that the lifetime of small particles in the disk is shortened by radiation pressure blowout. In any event, at β Pic, a wide range of particle sizes is indicated. At Vega, Mauron & Dole (1998) attempted to detect the dusty disk via optical photopolarimetry, but they were unsuccessful. Nonetheless, they were able to deduce that only a small percentage of the disk mass is carried by submicron grains of the sort that characterize the interstellar medium.

The most popular grain size distribution is a power law of the type assumed by Voshchinnikov & Krugel (1999), Krivova et al. (2000), and many others, where $n(a) \sim a^{-q}$, and, usually, $q \sim 3.5$. This may be related to the size spectrum corresponding to fragmentation processes. By analogy with the inner solar system, an alternative, more-complex particle size distribution might be that of Kyte & Wasson (1986: their Figure 4), where there is a peak in the particle number density around 100 μm. This peak is due to dust released by comets. The power law portion of the Kyte-Wasson mass spectrum only begins to dominate for particles of dimensions much larger than 100 μm.

5. THE FUTURE

Until the past few years, study of CS disks from the ground, with but few exceptions, has not been rewarding. Analysis of IRAS data obtained over 15 years ago has dominated the field. Recently, sensitive new array detectors at submillimeter wavelengths and in the mid-IR (10–20 μm) have finally enabled a suite of important ground-based discoveries. At about the same time, the NICMOS near-IR coronagraphic camera on the HST obtained stunning images of CS disks around a few young stars.

The coming decade promises great advances in ground-based, airborne, and space-based studies of CS disks. On the ground, millimeter interferometer arrays at high, dry sites in Hawaii and Chile will produce unprecedently detailed pictures of the structure of CS disks. The SOFIA airborne observatory will measure the spatial extent and spectrum of dust emission throughout the far-IR, where the CS disks around most Vega-like stars emit most intensely. And from space, SIRTF will enable detection of many new Vega-like systems that emitted too faintly for detection by IRAS. Many such systems may be discovered around stars of a solar mass or less that were mostly out of the reach of the IRAS.

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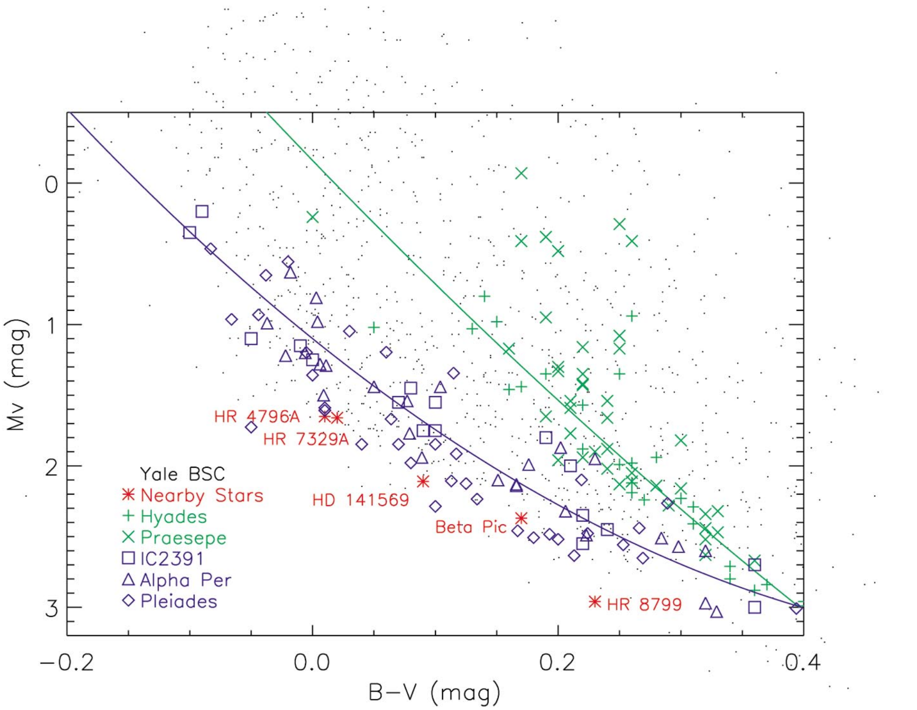

Figure 5 HR diagram for A-type stars (Lowrance et al. 2000). (*Lines*) Traces of the positions of stars in the older, Hyades/Praesepe clusters at ∼600 Myrs and the much younger, α Per/IC2391 clusters at ∼70 Myrs. Some of the named stars are discussed in the text. Very young ages for some are deduced from late-type companions. These named stars trace the zero-age main sequence for A-type stars.

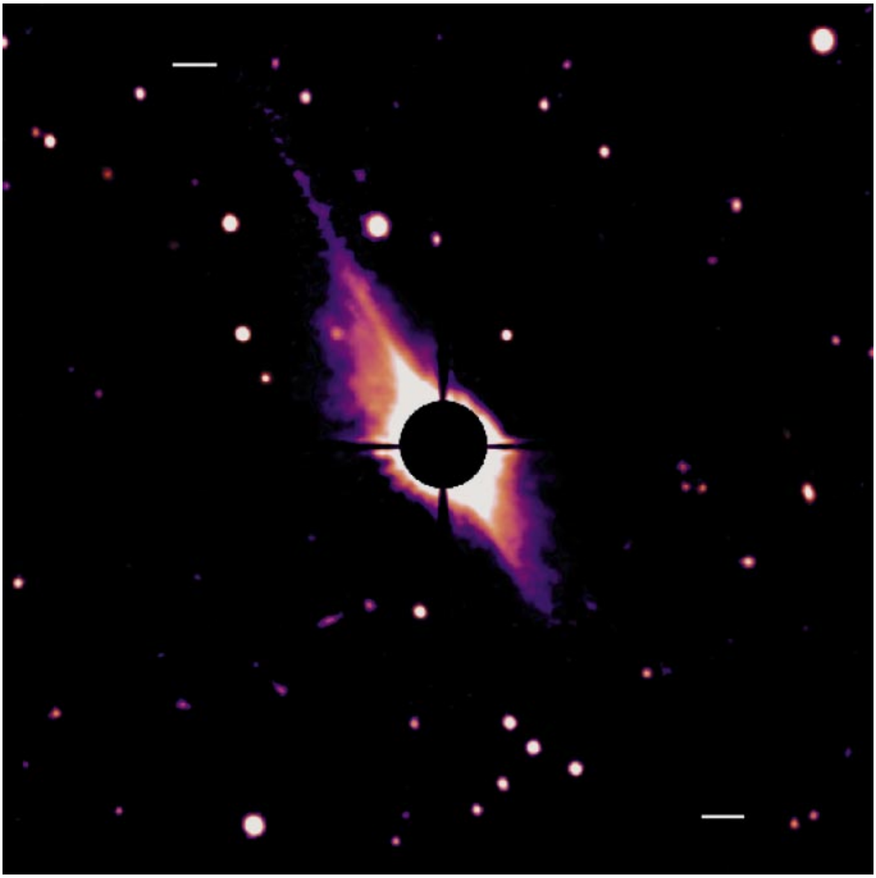

Figure 6 R-band coronagraphic image of β Pictoris obtained on the University of Hawaii 2.2-m telescope at Mauna Kea Observatory on 31 January 2000 (P. Kalas, personal communication). (*Top*) North; (*Left*) East; (*white bars*) represent 10 arcsec; the bars are located 2000 AU from β Pic. This image, obtained through three air masses, has been smoothed and "cleaned up" somewhat. The science quality image appears in Larwood & Kalas (2001). The northeast arm appears much longer than the southwest arm. But it is along the latter that the submillimeter emission peak appears 34 arcsec from the star (Figure 7b, see page C-3). There is no hint of this peak in the R-band data.

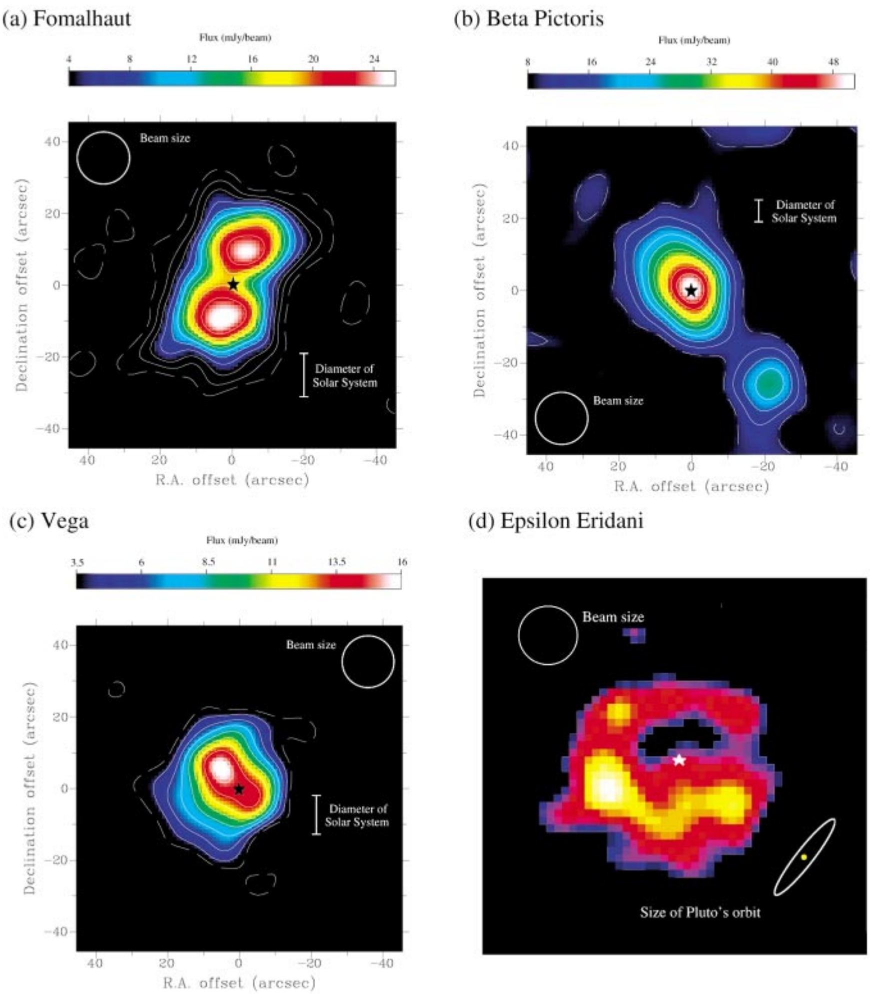

Figure 7 Dust emission around (*a*) Fomalhaut, (b) β Pictoris, (c) Vega, and (*d*) ϵ Eri at a wavelength of 850 μm. The images were obtained with the SCUBA bolometer array on the James Clerk Maxwell telescope (JCMT) (Holland et al. 1998; Greaves et al. 1998). (*Top*) North; (*Left*) East; (*star symbol*) location of the star; (*circle*) diameter of the JCMT beam at half power.