

COMETARY DUST IN THE DEBRIS DISKS OF HD 31648 AND HD 163296: TWO “BABY” β PICTORIS STARS

MICHAEL L. SITKO¹

Physics Department, University of Cincinnati, Cincinnati, OH 45221

CAROL A. GRADY

Eureka Scientific, 2452 Delmer Street, Suite 100, Oakland, CA 94602

DAVID K. LYNCH¹ AND RAY W. RUSSELL¹

Aerospace Corporation, Los Angeles, CA 90009

AND

MARTHA S. HANNER¹

Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA 91109

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ABSTRACT

The debris disks surrounding the pre-main-sequence stars HD 31648 and HD 163296 were observed spectroscopically between 3 and 14 μm . Both stars possess a silicate emission feature at 10 μm that resembles that of the star β Pictoris and those observed in solar system comets. The structure of the band is consistent with a mixture of olivine and pyroxene material, plus an underlying continuum of unspecified origin. The similarity in both size and structure of the silicate band suggests that the material in these systems had a processing history similar to that in our own solar system prior to the time that the grains were incorporated into comets.

Subject headings: accretion, accretion disks — circumstellar matter — comets: general — stars: individual (HD 31648, HD 163296) — stars: pre-main-sequence

1. INTRODUCTION

It is now known that a large fraction, perhaps most, of all main-sequence stars possess significant amounts of refractory materials long after their formation (Aumann 1988). Originally discovered through their excess infrared emission, this “Vega phenomenon” has spurred many recent observational investigations into the formation and evolution of protostellar disks similar to that which our own Sun once had, which still remains in the form of interplanetary debris (dust, comets, etc.).

The star β Pictoris is the best studied example of a main-sequence star with an extrasolar debris disk. The disk, which is viewed edge-on, extends hundreds of AU and has a central clearing and warpage that may signal the presence of one or more Jovian planets. The colors of the disk are relatively neutral at visible wavelengths (Paresce & Burrows 1987), which suggests that the grains must be generally larger than 1 μm . The disk of β Pic is also polarized at about 17% (Gledhill, Scarrott, & Wolstencroft 1991), similar to the zodiacal light of our own solar system (Leinert et al. 1982), which suggests that the dust in the β Pic disk includes grains similar to solar system interplanetary dust particles (IDPs), including large (say, 10 μm diameter) fluffy aggregates of submicron size components. Therefore in many ways the dusty debris disk in β Pic is similar to that in our solar system, but it is more massive and presumably younger. Unlike the zodiacal light in the solar system where the band/continuum ratio is about 1.15 (Reach et al. 1996), β Pic exhibits a silicate emission feature with a band/continuum ratio of about 2 (Telesco & Knacke

1991) that requires a significant population of grains smaller than a few microns. Since such small grains will be easily removed by radiation pressure, they must be continuously replenished by the erosion of larger bodies. The emission of these small grains provides a means by which the mineralogy of the debris disk may be studied.

The shape of the IR spectrum of β Pic (Knacke et al. 1993) is similar to that of some solar system comets in the sense that both have silicate emission features at 10 μm , including a subfeature at 11.2 μm due to crystalline olivine. Furthermore, Bradley, Humecki, & Germani (1992) have identified the same spectral signature in a subclass of IDPs that consist of porous chondritic glassy silicates with embedded crystalline material. Some of the subcomponents of these grains consist of glasses with embedded metal and sulfides whose physical and chemical structure suggest extensive cosmic-ray exposure in the interstellar medium or in the protostellar nebula (Bradley 1994a, 1994b). Thus the debris disk of β Pic and the solar nebula (and by inference other protostellar disks) exhibit many of the same spectral characteristics and may have undergone similar evolutionary processes. To understand better how β Pic and other main-sequence stars with debris disks evolved into their present state, we need to investigate their evolutionary precursors.

The immediate evolutionary precursors of the Vega-like stars are the T Tauri stars for solar-mass stars and Herbig Ae/Be stars (HAEBEs) for more massive stars such as β Pic. Classic HAEBEs contain emission lines in their spectra, lie in regions of star formation that include “obvious” obscuration due to dust, and illuminate nearby reflection nebulae (Herbig 1960). They also possess infrared excesses longward of 1 μm . However, it has become apparent that there are a number of sources that have all the spectral characteristics of the classic HAEBEs but are not embedded in dusty

¹ Visiting Astronomer, Infrared Telescope Facility, operated by the University of Hawaii under contract with the National Aeronautics and Space Administration.

regions. Many are probably intermediate-age objects that are not yet main-sequence stars but are generally older than the classical HAEBEs: post-HAEBEs (PHAEBEs). Many exhibit evidence of sporadic accreting material (Grady et al. 1996) similar to that of β Pic, and in one case, HD 100546, the data are consistent with star-grazing comets (Grady et al. 1997).

Mannings & Sargent (1997) and Mannings, Koerner, & Sargent (1997) have mapped the thermal dust millimeter-continuum and gaseous CO emission in HD 31648 and HD 163296, two stars that would be classified as PHAEBEs. For HD 163296, deconvolution of the maps of the CO emission indicates a disklike structure that has a radial extent of 310 AU. The dust has a radial extent of 110 AU (half-width at half-maximum, or HWHM). For HD 31648, the dust disk has an extent of 85 AU (HWHM). Both objects have accurate distances from the *Hipparcos* database, with HD 31648 at 131 pc and HD 163296 at 122 pc (both are uncertain by about 20 pc). These disks are much more massive than that of β Pic and the other Vega-like main-sequence stars and may provide a glimpse of what they and our own solar system may have been like during their later stages of formation.

2. OBSERVATIONS

IR spectra of HD 31648 and HD 163296 were obtained with the Aerospace Corporation’s Broadband Array Spectrometer System (BASS), which was configured to $f/35$ at the 3 m NASA Infrared Telescope Facility (IRTF). The BASS consists of a pair of cooled prisms that disperses the spectrum onto two 58 element blocked impurity band (BIB) linear arrays that simultaneously span the 3–13.5 μm region. The spectral dispersion ranges from about 30 to 125 over each of the 3–6 and 6.5–13.5 μm regions. At the IRTF, the BASS entrance aperture subtends $3''.4$. The observations reported here were obtained on 1996 October 14 (UT) along with observations of comet Hale-Bopp as part of a group of long-term programs to observe the spectra of pre-main-sequence stars and solar system comets. The spectra were flux calibrated using observations of standard stars at nearly the same airmass and time. For HD 163296 and Hale-Bopp, observations of Vega (which has no detected excess emission in the wavelength region covered here) were used. For HD 31648, Aldebaran was used. Details of the observations are listed in Table 1, and the resultant spectra of the two program stars are shown in Figure 1, where we have plotted the spectral flux (λF_λ in W m^{-2}) of the program stars. The BASS spectra of comet Hale-Bopp are discussed elsewhere (Hanner et al. 1998; Russell et al. 1998).

It is quite apparent that the spectra of these two stars are quite similar. Both objects possess emission by warm dust

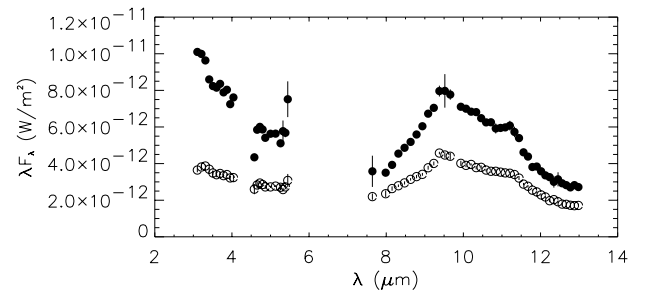


FIG. 1.—Flux of HD 31648 (*open circles*) and HD 163296 (*filled circles*)

down to 3 μm and a well-defined silicate emission band near 10 μm , features that are common in many pre-main-sequence stars accompanied by dust. In the following section, we shall examine how the data on these two stars compare to that of β Pic, solar system comets, and laboratory spectra of relevant materials.

3. COMPARISON WITH β PIC, SOLAR SYSTEM COMETS, AND LABORATORY MEASUREMENTS

β Pic has an emission band that rises up to a local maximum near 9.5 μm , is nearly flat-topped to 11.2 μm , then falls off to the local continuum (Knacke et al. 1993). This sort of “trapezoidal” silicate emission is also present in the spectra of many, but not all, solar system comets (Hanner, Lynch, & Russell 1994). When normalized in a similar fashion (see, for example, Fig. 6 of Knacke et al. 1993), the short-wavelength peak appears somewhat higher in β Pic than in the comets.

The feature near 11.2 μm deserves special attention because it is indicative of the presence of crystalline olivine. This feature is also seen in the outflows of some evolved stars where dust is condensing (Waelkens et al. 1996) but is not a general feature of the dust in either star-forming regions or diffuse interstellar clouds. If we see it in comets and β Pic, where is it made?

Since crystalline olivine condenses at the high temperatures (greater than 1200 K) that might have been typical of the inner solar nebula, it could, in principle, have formed by condensation during the formation of the solar system. This scenario requires that these grains then be transported to the region of comet formation and be mixed with ice grains that probably condensed at temperatures below 30 K (Crovisier et al. 1997). How this is accomplished is not fully understood. Similarly, more amorphous grains may have undergone annealing in the solar nebula, but again they would need to be efficiently transported out to

TABLE 1
OBSERVING PARAMETERS

Star	Mean UT	Mean Airmass	Number of Spectra	Integration Time (minutes)
HD 163296	0540	1.98	3	10.0
Comet Hale-Bopp.....	0610	2.08	5	16.7
α Lyr	0645	1.92	3	10.0
HD 31648	1008	1.58	5	16.7
α Tau	0946	1.61	3	10.0

the region of comet formation. In any case, such grains do exist in solar system comets, and examining the development of these features in other stellar systems may give us clues as to how it was accomplished in our own solar system.

Until recently the evidence for comet-like silicate emission features in other pre-main-sequence stars was scarce. Using data primarily from the *IRAS* Low Resolution Spectrometer database, the majority of HAEBEs and PHAEBEs exhibit little spectral structure in the silicate band (see Sitko et al. 1994, for example); however, in the past 2 years a considerable mass of evidence clearly indicates that this conclusion may have been biased by studying very young objects whose dust has undergone little physical and chemical processing since the disk formed. The intermediate-age objects appear to exhibit spectral structure that may correlate with the degree of disk clearing (van den Ancker et al. 1997). HD 31648 and HD 163296 are the first of these intermediate-age higher mass stars, “baby” β Pics, to have resolved protostellar disks in both gas and dust emission, and both exhibit structure in their silicate bands similar to that of β Pic.

In order to compare the spectral characteristics of the young stellar debris disks with that of solar system dust, it is useful to compare the net emissivities of the dust in the silicate band region. As a first approximation, this can be done by dividing the observed flux by a gray body normalized to the continuum flux outside the emission band, as has been done in the past for cometary spectra (Hanner et al. 1994). In Figure 2, the spectra of HD 31648 and HD 163296 have been normalized to a gray body between 8 and 13.5 μm . Also shown are the emission spectra of comet Hale-Bopp (C/1995 O1), obtained within 30 minutes of the HD 163296 spectrum (and at the same airmass), and comet Levy (C/1991 L3; Lynch et al. 1992), treated in the same fashion.

All four spectra possess similar characteristic features. They all have a general trapezoidal shape that reaches local maxima near 9.5 and 11.2 μm , and all are relatively flat-topped between those wavelengths. The band/continuum ratio in this region is between 1.5 and 2.5 for all four objects. The silicate feature in HD 31648 has both the same strength and shape as comet Levy from 10 to 13 μm and differs only in having a slightly greater emission at the short-wavelength wing. Similarly, the band emission in HD 163296 also shows excess emission at 9.5 μm compared to comets, as shown in Figure 3, where it is compared to the profile of Hale-Bopp after removal of the underlying continuum (as was done for β Pic in Fig. 6 of Knacke et al. 1993).

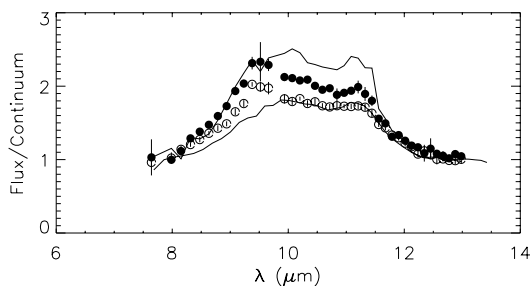


FIG. 2.—Flux/continuum ratio for HD 31648 (open circles) and HD 163296 (filled circles) compared to that of comet Hale-Bopp (upper curve) and comet Levy (lower curve).

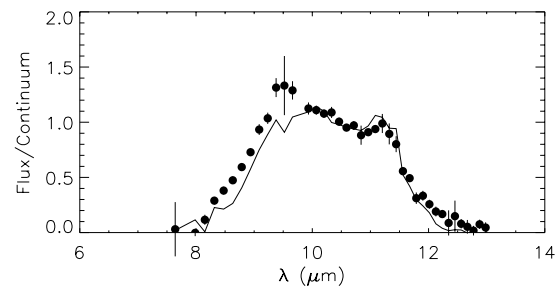


FIG. 3.—Spectrum of HD 163296 and comet Hale-Bopp after removal of the underlying continua and scaled to the same approximate strength in the middle of the band.

While the 9.5 μm feature sits in the middle of the telluric ozone band and is subject to greater uncertainty than most of the rest of the emission profile, we believe this difference is real. First, the error bars shown are simple standard deviations, which tend to overestimate the true uncertainty of the mean value (the standard deviation of the mean). More importantly, such a difference can arise from systematically having different ozone opacity for the HAEBEs compared to their calibrators, but this is unlikely to be the source of the difference seen here for two reasons. First, in the case of HD 163296 the data for the star and Hale-Bopp were obtained through nearly the same airmass, at about the same time, and calibrated with respect to the same standard star observation. Second, *the peak at 9.5 μm is seen in many of these objects* (Sitko et al. 1998). Furthermore, the same difference seems to be present in the spectrum of β Pic.

It is instructive to compare the spectra of the dust in these systems to those of silicate materials measured in the laboratory. Stephens & Russell (1979) have measured the relative emissivity of pyroxene and olivine in both glassy and crystalline forms. The glassy material was obtained by laser-vaporization of mineral samples. The resultant condensate smoke was allowed to settle on a copper block. Crystalline samples were prepared by grinding the mineral material and allowing them to be deposited on a copper block. The emissivity was then determined by heating the block plus sample and measuring the resultant spectrum. The material used was Mg-rich olivine and enstatite [specifically $(\text{Fe}_{0.07}\text{Mg}_{0.93})_2\text{SiO}_4$ and $(\text{Ca}_{0.01}\text{Fe}_{0.11}\text{Mg}_{0.88})\text{SiO}_3$, respectively]. The ground particles were generally less than 5 μm in size, while the median diameter of the condensed glassy smokes was about 0.02 μm . The resulting emissivities of these four materials are shown in Figure 4.

In Figure 5, we compare the emission spectrum of HD 163296 with the emission spectrum of a simple model consisting of glassy enstatite, glassy olivine, and crystalline olivine. To this we have added a continuum source with an emissivity of unity (a blackbody). For simplicity, the same temperature, 440 K, was assumed for all components. Crystalline olivine is required to fit the 11.2 μm feature, and glassy enstatite is needed for the short-wavelength wing of the band. The continuum source with $T = 440$ K is required to provide the underlying continuum flux and its spectral slope. The source of the continuum could be virtually any featureless material. Finally, some other component is needed for the middle of the band (crystalline enstatite could also work here, although it is a much narrower component). Given the simplistic nature of this

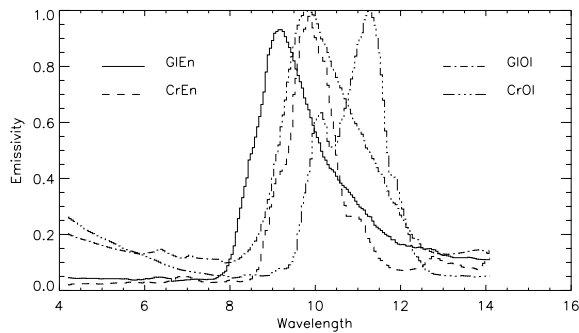


FIG. 4.—The emissivities of glassy enstatite (solid line), crystalline enstatite (dashed line), glassy olivine (dot-dashed line), and crystalline olivine (triple-dot-dashed line), measured in the laboratory by Stephens & Russell (1979).

model (using a few end types of dust materials), the emission observed in HD 163296 is reproduced reasonably well by the model; however, the observed emission in this object (and by inference other HAEBEs with similar spectra, such as HD 31648) probably requires an additional component to explain the additional emission observed near $9.4 \mu\text{m}$. It is likely that this is some form of pyroxene material. While we have restricted our fit to only one specific material, pyroxenes come in a wide variety of forms. Although the olivine-dominated IDPs studied by Sanford & Walker (1985) all had very similar spectra, no two pyroxene IDPs were identical.

4. DISCUSSION

Overall, the spectral emission of these stars resembles those of “typical” solar system comets, which suggests that the dust in these systems may have undergone a history of processing similar to that of our own solar system prior to when the dust material was incorporated into comets such as Halley and Levy. The majority of comets with well-defined silicate emission bands are long-period objects (Halley, though strictly short-period, has an inclination more like long-period objects) and presumably arise from the Oort cloud. In turn, these objects are believed to have arisen in the Uranus-Neptune region before being scattered outward (and inward) by planetary perturbations. The silicate band in the short-period comets, whose origin is in the Kuiper belt, is smaller than that seen in HD 31648 and HD

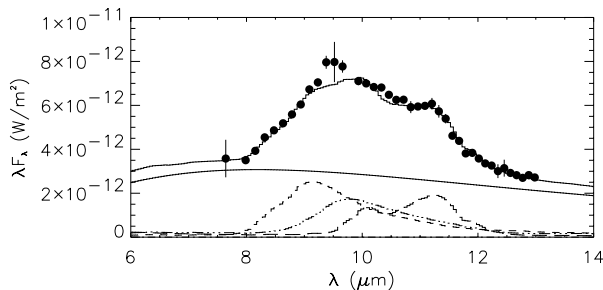


FIG. 5.—Spectrum of HD 163296 compared to a model comprised of glassy enstatite, glassy olivine, crystalline olivine, and an underlying blackbody continuum component (all at $T = 440 \text{ K}$).

163296, having band/continuum ratios of only 1.25 or less (Hanner et al. 1996).

In HD 31648 and HD 163296 the lifetime against radiation pressure and Poynting-Robertson drag for grains small enough to exhibit the silicate band in emission is about a century (see Sitko et al. 1994), using the luminosities and masses of these stars (Mannings & Sargent 1997). Thus, we are presumably seeing the emission of some time-integrated (over about a century) ensemble of cometary debris. The ratio of luminosities of the dust emission of HD 163296 to that of the inner coma of Hale-Bopp, using the $4'3$ aperture, between 8 and $13 \mu\text{m}$, is 3×10^{14} . Thermal infrared images of Hale-Bopp (Hayward & Hanner 1997) indicate that a much larger aperture would reduce this ratio by an order of magnitude to a few times 10^{13} . A similar ratio was obtained by Malfait et al. (1998) for the PHAEBE star HD 100546 with respect to Hale-Bopp using the *Infrared Space Observatory's* Short Wavelength Spectrometer (ISO SWS) for both objects. (The ISO SWS entrance aperture is $8'' \times 20''$.) A few totally disintegrated Chiron-sized objects would also have sufficient mass to produce the observed emission if the silicates were in small grains. Whether we are actually seeing the silicate emission from the comet, tails, and older zodiacal debris of trillions of cometary-sized objects or of a few disrupted larger ones is not known. If it is the latter, it should be possible to detect changes in the band strength and shape over timescales of years or less, possibly accompanied by flux variability at visible and ultraviolet wavelengths. One such event may have been recently detected in the candidate PHAEBE star HD 45677 (Sitko et al. 1994).

Like β Pic, many of the HAEBEs and PHAEBEs exhibit optical and ultraviolet spectral features indicative of infalling evaporating objects, such as comets or asteroids (Grady et al. 1996, 1997; Pérez & Grady 1997), some of which require star-grazing orbits. HD 163296 exhibits such infall events (Grady et al. 1998), but these are not observed in HD 31648, presumably because of its higher disk inclination (30° vs. 58° for HD 163296, where 0° is pole-on; Mannings & Sargent 1997; Mannings, Koerner, & Sargent 1997). Such orbits may require the presence of gravitationally perturbing bodies, such as Jovian planets. Mannings & Sargent (1996) have estimated the ages of HD 31648 and HD 163296 as 6 and 5 Myr, respectively. In the case of the solar nebula, this would correspond to well after the formation of planetesimals and even Jupiters (Wetherill & Stewart 1993; Cameron 1995; Pollack et al. 1996). Such star-grazing objects are now routinely detected in our own solar system by using satellites with coronagraphs (such as *SOHO*), and must have been much more common during the more lively early bombardment period of the solar system. Since we are presumably observing HD 31648 and HD 163296 during a similar epoch, such infall events and the production of cometary silicate emission features is expected.

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