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The Dust in β Pictoris Systems

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Abstract.
The bright 10 μm excess emission of β Pic stars allows detailed spectroscopy of their warm circumstellar solid material. The silicate features in β Pic and 51 Oph are broader and contain more structure than interstellar and most circumstellar emission features. The β Pic and 51 Oph features are remarkably similar to those in comets Halley, Bradfield 1987s, Levy 1990 XX, and Mueller 1993a which have 11.3 μm emission features characteristic of crystalline silicates. In contrast, other β Pic-type stars (ζ Lep and β UMa) show weak 10 μm emission from larger, amorphous dust grains. Some comets such as Austin 1990 V emit similar weak 10 μm features.

1. Introduction

To date, there are more than 100 main-sequence stars of all spectral types with IRAS excesses (review by Backman & Paresce 1993). Among them, β Pic (A V) and other systems show substantial (comparable to or greater than the photospheric flux) warm dust excess emission in the IRAS 12 μm bandpass. These excesses are thus accessible for ground-based follow up at $\sim$ 10 μm. Telesco & Knacke (1991, hereafter TK) discovered circumstellar silicate emission from β Pic. The broadband fluxes suggested a strong resemblance to the emissivity of Comet Halley (Campins & Ryan 1989). Knacke et al. (1993) and Aitken et al. (1993) subsequently obtained spectroscopy of β Pic, confirming the analogy with comet Halley's silicates. Fajardo-Acosta, Telesco, & Knacke (1993, hereafter FTK) detected silicate emission from 51 Oph (B9.5 V). Russell et al. (1995) obtained spectroscopy of 51 Oph and confirmed the similarity of 51 Oph silicates to those of β Pic. Other main-sequence stars with measured mid-infrared spectra, such as HD 98800, K5 V (Skinner, Barlow, & Justtanont 1992) and SAO 26804, K2 V (Skinner et al. 1995), have fainter excesses that are more difficult to characterize. Fajardo-Acosta et al. (1995) obtained 10 μm spectra of two systems with modest excesses ($\sim$ 10% of the photospheric flux): β UMa (A1 V) and ζ Lep (A3 V). In this paper I discuss whether the silicates in β Pic (Section 2), and 51 Oph (Section 3), resemble those in β UMa, and ζ Lep (Section 4).

2. The Silicates in β Pictoris

The mid-infrared spectrum of β Pic (Knacke et al. 1993) is shown in Figures 1a–f (filled circles) together with photometry of β Pic in the "silicate" filters

(TK, open circles; Fajardo-Acosta & Telesco 1995, open squares).

The 10 μm silicate emission feature of β Pic is broad and flat-topped, with a prominent peak at 9.5 μm, and possibly another at 11.3 μm. To investigate the nature of these spectral features we compare β Pic's spectrum with those from other astronomical environments and laboratory samples (Figures 1a–f).

2.1. The 9.5 μm Peak

Figure 1a compares a model emission spectrum (solid line) of "astronomical" or interstellar medium Draine & Lee (1984) silicate spheres of 0.1 μm radius and the β Pic spectrum. The Draine & Lee model in Figure 1a cannot reproduce the structure at $\sim$ 11 μm in β Pic's feature. However, the Draine & Lee model is a good match to the 9.5 μm peak in β Pic. This peak resembles those from amorphous silicates (Figure 1b, Day 1979) or hydrated (layer-lattice) ones (Zaikowski & Knacke 1975).

2.2. The 11.3 μm Peak

We investigated fits of the spectra of other minerals to the $\sim$ 11 μm structure in β Pic's feature. In Figure 1c we show the normalized Q_{ext} of crystalline olivine (Koike et al. 1981). This feature is too narrow to match β Pic's. But the position of the 11.3 μm peak is perfectly matched.

2.3. IDP's, Comets, and β Pic

The presence of both 9.5 μm and 11.3 μm peaks in β Pic's silicate feature suggests β Pic dust is a mixture of amorphous and/or hydrated silicates and crystalline olivine. The silicate features of interplanetary dust particles (IDP's) and some comets imply a similar dust composition (Campins & Ryan 1989, among others). Sandford (1988) constructed a composite of IDP spectra (Figure 1d). This spectrum includes a 55% contribution from olivines, 35% from pyroxenes, and 10% from layer-lattice silicates. The composite IDP particle spectrum fits the β Pic spectrum quite well.

Figure 1e compares β Pic's silicate feature and those from comets Halley (Campins & Ryan 1989) and Levy 1990 XX (Lynch et al. 1992). The analogy between β Pic's and these comets' features is remarkable (Knacke et al. 1993). The spectra of comets Bradfield 1987s (Hanner et al. 1990) and Muller 1993a (Hanner et al. 1994) are also very similar to β Pic's.

2.4. Comparison with LRS Spectra

The Atlas of IRAS Low Resolution Spectra (1986) consists of 8–22 μm spectra of 5425 sources. Many LRS spectra show 10 μm silicate features. Knacke et al. (1993) showed that 88 of the 5425 LRS sources (or 1.6%) show silicate features that match β Pic's. Figure 1f shows the smoothed mean profile of the 88 selected LRS spectra. Many of the sources have no spectral associations in catalogs. Those that do are typically asymptotic giant branch stars with dust shells. It is intriguing that these late-type stars, presumably a birthplace of interstellar silicate grains, emit spectral features similar to those in β Pic and solar system material (Knacke et al. 1993). Fajardo-Acosta & Knacke (1995) review the possibilities that AlO or crystalline olivine emit the 11.3 μm structure in the 88

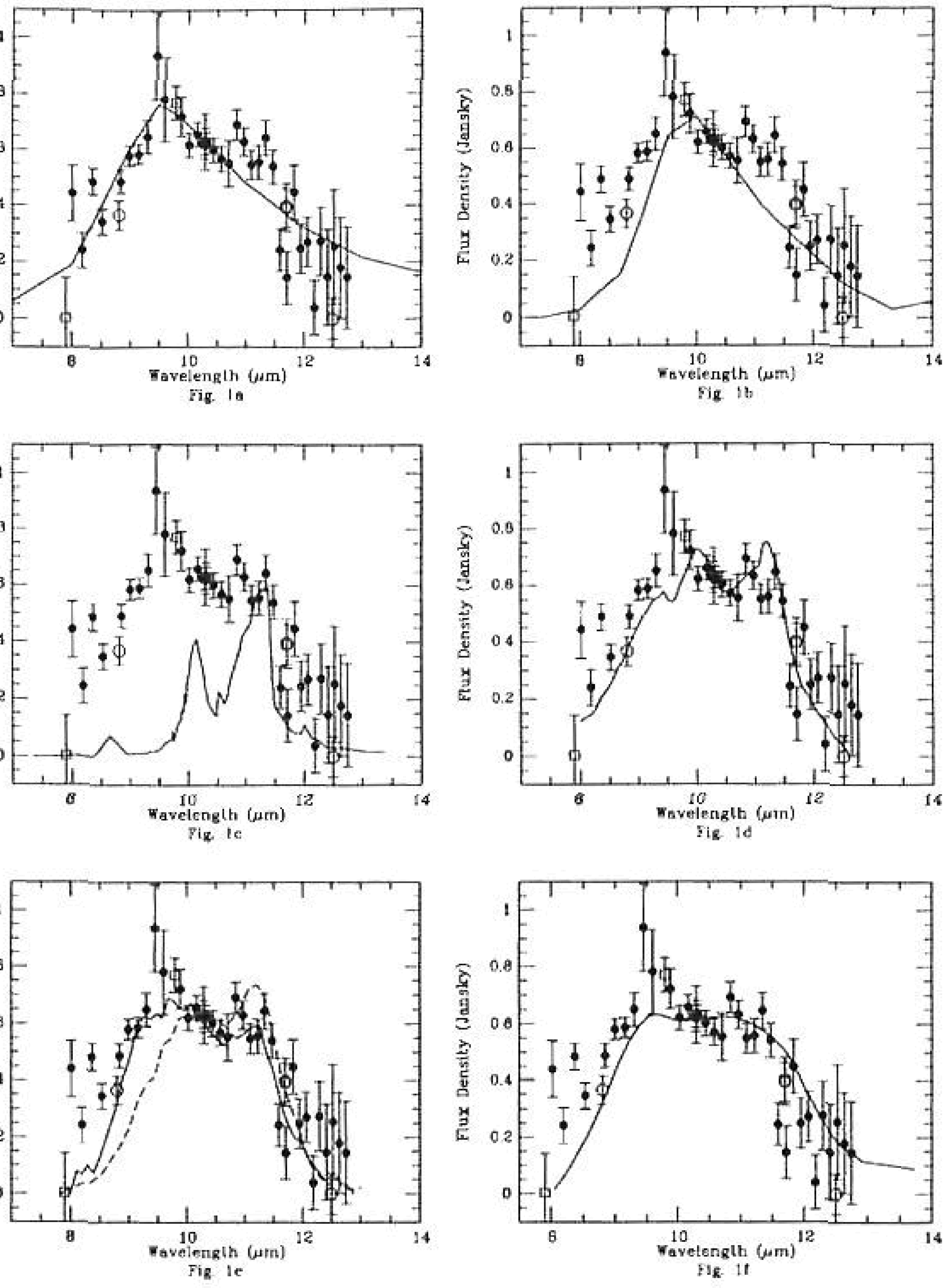

Fig. 1 Comparison of β Pic's spectrum (Knacke et al. 1993,*filled circles*) and photometric data (TK, *open circles*; Fajardo-Acosta & Telesco 1995, *open squares*), minus photospheric and dust continua, with (a) a model emission spectrum of 0.1 μm "astronomical" silicate dust grains (Draine & Lee 1984); (b) Q_{abs} of amorphous, vapor-condensed Mg-silicate spheres of 0.1 μm radii (Day 1979); (c) the normalized Q_{ext} of crystalline olivine (Koike et al. 1981); (d) a composite spectrum of interplanetary dust particles (Sandford 1988); (e) spectra of Comet Halley (Campins & Ryan 1989), *solid line*, and Comet Levy 1990 XX (Lynch et al. 1992), *dashed line*, minus dust continua; (f) the smoothed mean profile of 88 LRS spectra with good fits to the β Pic spectrum (Knacke et al. 1993).

LRS spectra and they conclude that crystalline olivine provides a better fit.

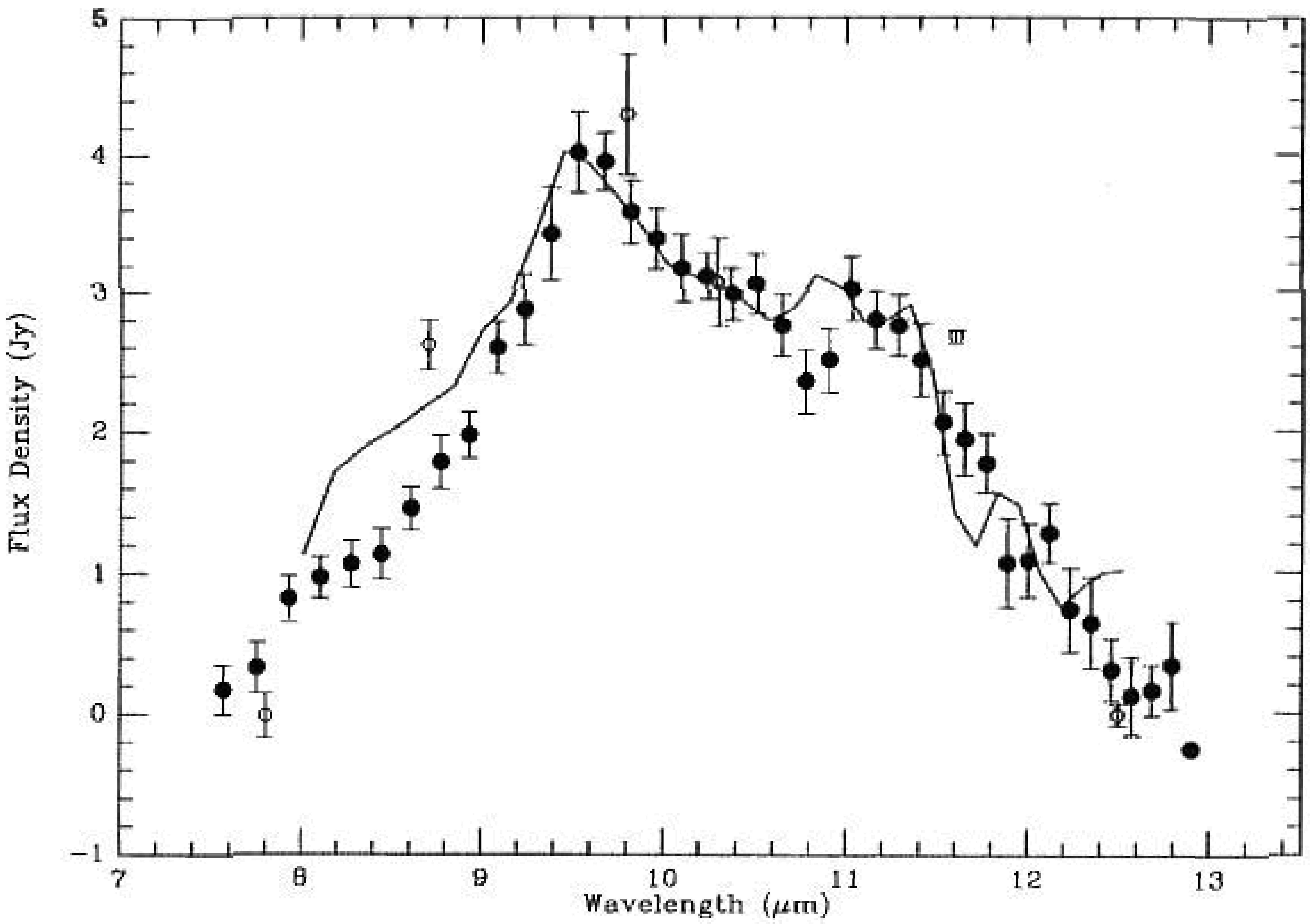

Fig. 2 Spectrum of 51 Oph (Russell et al. 1995, *filled circles*), and photometric data (FTK; *open circles*). A 9500 K photospheric continuum (Waters et al. 1988) and a 500 K dust continuum (FTK) have been subtracted from these data. For comparison, the *solid line* is the spectrum of β Pic (Knacke et al. 1993) as in Figures 1a–f. It was smoothed by averaging adjacent channels, and it was renormalized at 10.38 μm.

3. Silicates in 51 Ophiuchi

Following the detection of a silicate feature in 51 Oph (FTK, Figure 2, open circles), Russell et al. (1995) obtained a spectrum of 51 Oph (Figure 2, filled circles). Sylvester, Barlow, & Skinner (1995) obtained a comparable spectrum at 7.5–23.5 μm. Figure 2 also shows a smoothed version of the spectrum of β Pic.

Figure 2 shows how similar the widths and peak wavelengths of the emission features are in 51 Oph and β Pic. As is the case of β Pic, the silicate feature of 51 Oph shows a prominent peak near 9.5 μm, and a secondary peak at $\sim$ 11.3 μm.

The spectral similarity of silicates in β Pic and 51 Oph implies the latter also resemble those of comets such as Halley. This result strengthens the conjecture that comet-like bodies resupply the dust in β Pic (Weissman 1984), and therefore also in 51 Oph. The spectral structure at $\sim$ 11 μm in β Pic and 51 Oph, if attributed to crystalline olivine as in several comets, indicates their silicates must have been thermally processed into crystalline forms when or before they were incorporated into cometary bodies (see Knacke et al. 1993 for the case of β Pic).

4. Infrared Spectroscopy of Other β Pictoris Systems

We carried out mid-infrared photometry (Fajardo-Acosta & Telesco 1995) and spectroscopy (Fajardo-Acosta et al. 1995) of other β Pic systems. These obser-

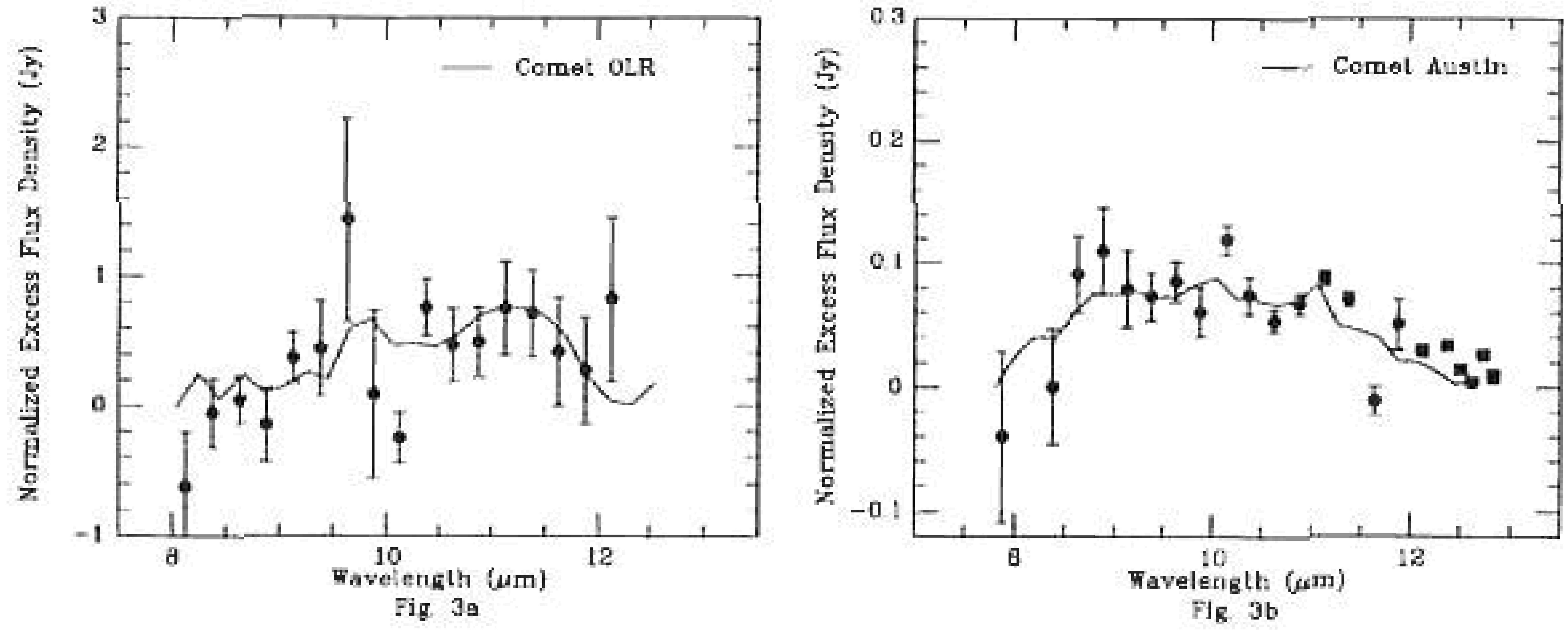

Fig. 3 (a) Spectrum of β UMa (Fajardo-Acosta et al. 1995, *filled circles*), after subtraction of a 9500 K photospheric continuum. The flux at 9.6 μm is probably affected by terrestrial ozone. The *solid line* is the spectrum of comet Okazaki-Levy-Rudenko (Russell & Lynch 1990) minus a 370 K dust continuum. The comet spectrum was normalized at 11 μm to β UMa's one. (b) ζ Lep fluxes after subtraction of 9250 K photospheric and 215 K dust continua (Fajardo-Acosta et al. 1995, *filled circles*). The spectrum of comet Austin 1990 V (Hanner el al. 1993, *solid line*) is also shown for comparison. A 300 K dust continuum was subtracted from the comet spectrum, and it was fit at 9.46 μm to ζ Lep's flux.

vations show that prominent silicate emission, such as in β Pic and 51 Oph, is otherwise not common among other systems. Two of the sources we observed (β UMa and ζ Lep) showed weak but definite excess flux at 10 μm.

Figure 3a shows the excess spectrum of β UMa (filled circles). This spectrum possibly exhibits an excess (S/N $\sim$ 2) between 10 and 12 μm. Figure 3a (solid line) also shows the spectrum of the "dust poor" comet Okazaki-Levy-Rudenko 1989 XIX (OLR, Russell & Lynch 1990). Comet OLR has a weak emission feature centered at $\sim$ 11 μm possibly similar to that in β UMa. Hanner, Lynch, & Russell (1994, HLR) noted that OLR's feature might be produced by large grains. The same could be true of β UMa's weak emission feature.

Figure 3b shows the excess spectrum of ζ Lep (filled circles). The presence of excess at wavelengths shorter than 9 μm indicates very hot dust close to the star. The emission feature in ζ Lep is weak and broad, and it does not resemble a silicate feature. Figure 3b (solid line) also shows the spectrum of the "dust poor" comet Austin 1990 V (Hanner et al. 1993). Comet Austin's spectrum shows a very broad 8–12.5 μm shallow feature, possibly due to an assemblage of amorphous minerals of several types (HLR).

Our observing sample, however limited, suggests a parallel between the range of dust emission features seen from comets (reviewed by HLR), and from circumstellar dust of young main-sequence stars. On one hand we see prominent silicate emission from small, crystalline grains (as in β Pic and Comet Halley) and on the other we also see weak emission from possibly amorphous dust (as in ζ Lep and Comet Austin). This parallel is at present limited; some comets such as Wilson 1987 VII emit 10 μm features unlike those from any circumstellar or interstellar source (HLR).

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