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The β Pictoris Disk: Peculiar or Just Young?

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Abstract. The star β Pictoris is not in itself very remarkable; however, it is surrounded by a dust disk that is much more prominent than any other main sequence star's disk. The proximity of β Pic and the nearly edge-on viewing geometry of the disk enhance its appearance, but do not fully account for the disk's prominence. While it is possible that β Pic's disk is intrinsically unusual, a more likely explanation is that β Pic is simply a very young ($\sim$ 20 Myr old) main sequence star with a consequently denser second-generation debris disk remnant of its protostellar disk than possessed by older main sequence A stars.

1. Observations of the β Pictoris System

What is so special about the β Pic system? The excitement about β Pic began in 1983, when IRAS discovered a substantial mid- to far-infrared excess in the star's spectrum (Gillett 1986). Infrared excesses around main sequence stars are now known to be fairly common, but β Pic's IR excess is the brightest known and unusually large as a fraction of stellar luminosity (Backman & Paresce 1993).

Soon after IRAS, Smith & Terrile (1984) used a coronagraph to obtain an image at 0.89 microns of what appears to be a nearly edge-on disk around β Pictoris. The β Pic disk has since been imaged many times over a broad range of wavelengths, but in contrast, disks have only recently been imaged around a few other main sequence stars, and they appear far less spectacular. In fact, knowing the disk position angle, an observer can detect the β Pic disk at the eyepiece of a 2 – 3 meter telescope (R. Terrile, private communication). A favorable viewing geometry and location certainly are major factors in making the β Pic disk so photogenic, but nonetheless the disk must be intrinsically quite luminous.

A distance from *Hipparcos* of 19.3 ± 0.2 pc yields an absolute V mag of 2.42 ± 0.03 (Crifo et al. 1997) and thus a bolometric luminosity for β Pic of $8.5\,L_\odot$, given an effective temperature of 8200 K. Analysis of several photospheric lines (Ca II, Cr II, Fe II) indicate that the star has solar composition in metallic elements (Lanz et al. 1995; Holweger et al. 1997).

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Sub-mm photometry and an assumption of a plausible mass absorption coefficient led to an estimated total grain mass for the disk of 7×10^{23} kg ($\approx 0.1\,M_\oplus$) (Zuckerman & Becklin 1993). A silicate emission feature has been observed in β Pic's spectrum (Telesco & Knacke 1991); the details of this feature are more analogous to those seen in comets than to that of interstellar dust (Knacke et al. 1993). This supports the idea that the grains in the β Pic disk may be second generation, possibly of cometary origin, as was first claimed for the grains around α Lyrae (Weissman 1984).

High-redshift absorption lines which vary on time scales from hours to days have been observed around β Pic (Lagrange et al. 2000 and references therein). These absorption lines have been attributed to the comae of evaporating comets falling towards the star (falling evaporating bodies, or FEBs; Ferlet et al. 1987; Beust et al. 1990, 1991; Vidal-Madjar et al. 1994). The overall rate is estimated to be as high as a few hundred FEBs per year. Infall velocities of the well-studied Ca II lines range from 10 to 100 km/sec relative to the star, and the higher the velocity, the shorter the timescale of the variations. There is only a small number ($\leq 10\%$) of blueshifted events with respect to redshifted ones, a puzzling feature that seemingly demands a gross asymmetry in the system. Similar spectral features have been observed in Herbig Ae and Be stars (Grady & Silvis 1993, Grady et al. 1997), which are younger than β Pic.

More detailed reviews of the β Pic disk have been presented by Lissauer (1994), Artymowicz (1997) and Vidal-Madjar et al. (1998). For a discussion of β Pic in comparison to other dust disks around main sequence stars, see Lagrange et al. (2000) and Zuckerman (2001).

2. Comparison Between β Pic and Other Stars

Infrared surveys of various stellar samples reviewed and summarized in Backman & Paresce (1993) and Lagrange et al. (2000) indicate that at least 15% of A-K main sequence (MS) stars have some far-IR dust excess with fractional dust luminosity ($f_d \equiv L_d/L_\star$) greater than or equal to α Lyr's value of $\sim 2 \times 10^{-5}$. A few stars with f_d up to a few times 10^{-3}, comparable to β Pic, were found. Even larger values ($f_d \approx 0.1$ or more) were measured for some B–A stars which are also emission-line stars and thus probably pre-main sequence (PMS) or very young main sequence objects.

A coronographic optical imaging survey was performed on more than 50 MS stars and did not detect any more disks (Kalas & Jewitt 1995). The general non-detection of optical disks, even in the Vega and α PsA prototype IR-detected debris disk systems, is consistent with the small scattering cross-section of dust indicated by the IR spectral energy distributions (SEDs). The prominence of the β Pic disk therefore does *not* require that its grains are substantially different from grains around other stars.

HR 10, HR 2174 and 51 Oph exhibit narrow UV absorptions arising from excited levels indicating the presence of circumstellar gas at distances greater than $15\,R_\star$ (Dunkin et al. 1997; Lecavelier des Etangs et al. 1997a). Spectral monitoring of HR 10 (Welsh et al. 1998) confirmed variable redshifted absorptions (Lagrange-Henri et al. 1990) and moreover detected some blueshifted transients. Other attempts to detect circumstellar gas and/or spectroscopic variability were made in samples selected via IRAS (Cheng et al. 1992, 1995) and IUE criteria (Grady et al. 1996). A few stars were discovered to exhibit stable gas shell features, with 2 And also showing spectral variability in HST data (Cheng et al. 1997).

The old classification of β Pic as a shell star led to consideration of a possible link between B–A stellar shells and IR excesses. Among the 17 MS A-shell stars presently known and detected in the IRAS Faint Source Catalog, 4 have 12 μm excesses: β Pic, HR 9043, HR 3310 and HR 3989; the latter two stars are binaries. Cheng et al. (1991) found an IR excess for HR 10 using IRAS 1-dimensional coadds, and Fajardo-Acosta et al. (1998) detected a 20 μm excess around HR 2174. This yields 6 stars out of 17 with detected IR excesses, which is a fraction not much larger than that for ordinary field A stars.

The fact that at least 15% of nearby A, F, G, and K stars have far-IR dust excesses indicates that this phenomenon must extend at least in some cases over Gyr timescales. Nevertheless, a general decrease of f_d with age for PMS and MS objects is observed, discussed by Zuckerman & Becklin (1993), Holland et al. (1998), and Spangler et al. (2001). The similar A-type stars HR 4796A, β Pic, Fomalhaut, and Vega form a sequence of f_d decreasing monotonically from ages of 10 to 350 Myr.

The estimated overall dust grinding rate at the location of maximum dust density in β Pic's disk corresponds to a system destruction timescale of roughly 50 Myr, about 10^4 times longer than the disk replenishment time (Artymowicz 1997). This fits within the wide range of estimated ages for the star and is independent evidence that β Pic and its disk are not much older than 100 Myr. The total mass of the original β Pic planetesimal disk required for continuous dust replenishment is $\sim$ 100 $M_\oplus$, of order that originally present in our Solar System.

Young PMS stars (ages $\leq 1 - 10$ Myr, depending on mass) exhibit strong IR excesses and spectral features indicating many characteristic differences from the Vega/β Pic disks: 1) the disk masses may be as high as 0.01 $M_\odot$ for Herbig Ae/Be (HAeBe) stars (Natta et al. 2000); 2) accretion rates deduced from PMS disk SEDs are many orders of magnitude larger than the gas accretion rate in β Pic; 3) winds and other gas ejection evident in PMS systems from blueshifted lines and P Cygni profiles are not observed in Vega/β Pic systems; 4) photometric variability with amplitude as high as several magnitudes is observed in UX Ori-type objects (Natta et al. 2000), substantially more than the possible sporadic variability reported for β Pic.

A number of HAeBe stars have been reported by Grady et al. (2000) as exhibiting infall signatures superficially similar to those of β Pic. However, it is often difficult to disentangle stellar activity from genuine FEB signatures. For example, some of the PMS FEB candidate stars like AB Aur have variable spectral features that are attributable to differentially rotating and chromospherically driven winds or magnetically channeled accretion (Catala et al. 1993; Boehm & Catala 1995). There is also some evidence that the variability timescale is related to stellar rotation, supporting alternatives to FEB models. Therefore, application of the FEB hypothesis to a large number of HAeBe stars should be considered provisional at best.

A few stars (UX Ori, Grinin et al. 1994; HD 100546, Grady et al. 1997) show more convincing β Pic-like features, i.e., variable redshifted absorptions in metallic lines separable from features classically attributed to stellar activity. The variable features of ionized elements are similar to β Pic's in terms of shapes and velocity ranges, the infalling clouds have covering factors smaller than the stellar surface, and they contain over-ionized species (C IV, Al III). However, HAeBe variable absorption line events generally imply orders of magnitude more gas in the variable component than for β Pic.

Photometric and spectrophotometric data at $5 - 22\,\mu$m (Fajardo-Acosta et al. 1993) showed the presence of silicate emission attributed to grains smaller than $5\,\mu$m and with a total mass of silicates of $8 \times 10^{-5}\,M_{\oplus}$. The emission strength suggests that the typical grains around 51 Oph are larger and hotter than the ones around β Pic. The emission-feature mineralogy resembles that in β Pic and Solar System comets.

3. Planets in the β Pic Disk?

The interest in β Pictoris's disk is enhanced by theoretical arguments that planets form within dust/gas disks around young stars (Laplace 1796, Safronov 1969, Lissauer 1993). There is no direct evidence that β Pic possesses a planetary system. (Note that A stars have broad spectral lines, so they are not good candidates for radial velocity planet searches.) However, several pieces of indirect evidence support the hypothesis that one or more planets orbit β Pic.

The SEDs of the prototype circumstellar dust systems all imply transitions from outer high-density zones to inner low-density zones, but at so wide a range of temperatures that ice sublimation is an unlikely explanation for all of them. The dust density in the inner few tens of AU of the β Pic disk is far less than would be predicted by extrapolating the radial density gradient observed farther from the star (Backman et al. 1992; Golimowski et al. 1993). One or more planets may redirect or consume grains as they drift via Poynting-Robertson drag toward central stars (Roques et al. 1994).

Small photometric variations (≤ 0.06 mag) that occurred in 1981 were reported by Lecavelier des Etangs et al. (1995). The β Pic light curve, carefully monitored during several years for photometric calibration purposes by the Swiss ESO telescope, showed a brightening of 0.06 mag lasting about 10 days followed by a central drop a few hours long and then a return to the long-term average value. These variations were tentatively attributed to a planet or a giant comet cloud (Lecavelier des Etangs et al. 1997b; Lamers et al. 1997), but higher SNR, multiple wavelength studies over a long time baseline will be needed to confirm this hypothesis.

Kalas & Jewitt (1995) classified five varieties of asymmetry between the NE and SW wings in optical images of β Pic's outer disk: radial extent, surface brightness at a given radius, thickness at a given radius, and wing-tilt (position angle of the mid-plane), plus the so-called "butterfly" asymmetry in which disk thickness perpendicular to the mid-plane varies among the quadrants. The wing-tilt asymmetry can be explained by a combination of disk orientation and non-isotropic scattering phase function. The other surface brightness asymmetries must represent real dust density asymmetries that may reveal the dynamical influence of large masses in or near the disk.

The structure of the β Pic disk is the best understood of the prototypes due to high-resolution imaging. HST STIS imaging (Heap et al. 2000) has been joined by high-resolution Keck mid-IR images (Wahhaj et al. 2002; Weinberger et al. 2002) that together find warps and rings in the inner disk (within $r =$ 100 AU) that seemingly require the gravitational perturbation of several Jovian-mass companions. This is reminiscent of previous work by Whitmire et al. (1988) regarding the outer disk.

Nothing short of planetary gravitational perturbations seems adequate to explain the FEB triggering mechanism in the β Pic system. Possible mechanisms and their difficulties are reviewed in Lagrange et al. (2000). Some models require a planet on a highly eccentric orbit; others involve secular resonance perturbations produced by a planetary configuration like our Solar System (Levison et al. 1995). Interestingly, the 4:1 mean motion resonance is found to be an efficient and generic mechanism and one that can be an asymmetric source of star-grazing comets (Beust & Morbidelli 1999).

On a more theoretical basis, as planets presumably form within fairly massive circumstellar disks, the presence of a circumstellar dust disk around β Pic suggests that conditions may be (or more likely may have been, when the disk was more massive) appropriate for planetary growth. Giant planets in our Solar System are believed to have taken between a million and twenty million years to accumulate (Pollack et al. 1996; Hubickyj et al. 2002), whereas terrestrial planets may have required a bit longer (Wetherill 1990; Chambers 2001). Thus, if β Pic is $\sim$ 100 million years old, its planetary system is probably well-developed, but if the star is only $\sim$ 10 million years of age, its planetary system may still be undergoing rapid evolution.

4. The Age of β Pictoris

What process(es) accounts for the special aspects of β Pic discussed above? Pre-main sequence stars are commonly found with massive circumstellar dust disks, whereas older stars like our Sun have far less dust in orbit about them. β Pictoris's disk is anomalously massive for an A star that is even 10% of its main sequence lifetime old, but would not be unexpected around a very young main sequence A star. If β Pic is fairly young, say $\sim 10^7$ years, then it could be viewed as a transitional object between PMS stars that have massive optically thick disks and the much more tenuous collisional debris disks of older MS stars. Another possibility is that the β Pic disk was more substantial than most interstellar disks to begin with (or at the end of the epoch in which the star and any planets accreted), and has retained this excess as it has aged.

One problem with determining ages of stars via theoretical isochrones on an HR diagram is that the results are bi-valued, i.e., a star occupies a position above the Zero Age Main Sequence (ZAMS) both before and after the ZAMS. Although the distinction between MS and giant stars is usually straightforward, the distinction between MS and PMS stars sometimes is not, and this determination is more difficult for earlier spectral types. Theoretical stellar evolution calculations imply that A stars do brighten as they age, but proportionately much less than

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do low-mass stars, so this change is not a practical age diagnostic. A-type stars also lack the convective outer regions responsible for surface activity and gradual rotational slowing of smaller stars. The proximity of β Pic to the zero-age main sequence implies that its age lies between 14 Myr and 200 Myr, but uncertainties in its helium abundance, etc., prevent more restrictive estimates (Lagrange et al. 2000).

As β Pic does not lie near a known star forming region, the star is unlikely to be as young as a few million years. The best age for β Pic probably comes from comparison with two M stars that share its space velocity and have ages of 20 ± 10 Myr (Barrado y Navascues et al. 1999). These three stars' motion can be used to project them back to the Sco-Cen star formation region at about their derived age (Whitmire et al. 1992; Mamajek & Feigelson 2001). However, note that these M stars are 90 degrees away on the sky and 20 parsecs distant from β Pic. The low velocity of β Pic relative to the local standard of rest (Lissauer and Griffith 1989) also suggests that the star is young.

Is it unreasonable to expect that by chance such a young A star would be present so close to the Sun, i.e., does a young β Pictoris violate the Copernican Principle? It is statistically unlikely that any of the stars within 25 pc (twice the volume containing β Pic) are much younger than a few times 10 Myr. This result applies generally for all spectral classes and can be derived by dividing the lifetime of a typical member of each class by the number of stars in that class within the volume considered. Surveys of age indicators such as Li abundance and Ca II activity (e.g., Henry et al. 1996) show that the age histogram for nearby solar-type stars is approximately flat, with few objects younger than 10^8 yr.

Discovery of a number of stars apparently younger than 10 Myr in the TW Hya association (Webb et al. 1998) supports the above argument as this group lies at $d \approx 55$ pc and thus in a $10\times$ larger sample volume. The star HR 4796 has twice the dust optical depth of β Pic and is estimated from its pre-main sequence M dwarf binary companion to be ~ 8 Myr old. This A0V star at $d = 67$ pc has the highest IR disk fractional luminosity (5×10^{-3}) among MS A-type stars (Jura 1991; Jura et al. 1993). Spectroscopy of its nearer M-type companion (HR 4796B, $r \sim 500$ AU) gives an age estimate of $8 - 10 \times 10^6$ yr for HR 4796A, assuming the stars are physically linked (Stauffer et al. 1995; Jura et al. 1998).

The main sequence lifetime of mid-A stars is $\sim 1 - 2$ Gyr, so if the local star formation rate has been approximately constant and the stars were spatially well-mixed, then one can estimate that 1 – 2% of A stars are < 20 Myr old. There are 50 – 60 A stars within 25 parsecs (Cheng et al. 1995), roughly half closer to us than β Pic and half more distant. Thus, we are somewhat lucky to have β Pic so close, and quite lucky for it to be both close and viewed within 10° of edge-on, but the probability of these circumstances occurring by chance is not so small as to cast doubt upon the model.

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