LINKS BETWEEN DUST DISKS AND EXOPLANETS

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1. Abstract

Since 1984, roughly 100 main sequence stars within 50 parsecs of the Sun have been identified as possibly possessing replenished, circumstellar dust disks. Optical to submillimeter imaging has resolved disk-like structure around 7 main sequence stars. We review these results, and discuss how they elucidate the existence and properties of exoplanetary systems.

2. History of Replenished Dust Disks

One of the first published observations of a replenished dust disk linked to planets is provided by a ship's captain (Jacob 1859), who describes the orientation and disk-like shape of the Zodiacal light:

> *The light at its brightest was considerably fainter than the brighter portions of the milky way, and shaded off so gradually that its limit could hardly be guessed at within several degrees . . . The outline generally appeared of a parabolic or probably elliptical form, and it would seem to be excentric as regards the sun, and also inclined, though but slightly, to the ecliptic.*

Astronomical instruments that would permit astronomers to image exozodiacal dust disks appeared 80 years later with advances in solar astronomy. During the early 1900's, solar astronomers were faced with the challenge of producing an instrument that could observe the solar corona in the absence of a total eclipse. Lyot (1939) finally invented the solar coronagraph, consisting of an opaque occulting spot at the focal plane of the telescope, and a "Lyot stop" at the pupil plane to mask diffracted light. Apparently, the Lyot coronagraph was not utilized for other purposes, such as searching for faint companions to nearby stars. The possibility that exozodiacal dust clouds might be more readily detectable than exoplanets due to their greater surface areas also did not attract attention.

Thirty years later, unmanned interplanetary vessels had replaced the sea captains and studied the zodiacal dust cloud *in situ* (Leinert et al. 1976). Scientists developed a "planetary" coronagraph to observe Saturn's rings and moons in support of the Voyager spacecraft missions (Larson and Reitsema 1979, Jewitt et al. 1981). After the Infrared Astronomical Satellite (IRAS) revealed that Vega, Fomalhaut, ϵ Eri, and β Pic may be surrounded by dust clouds, Smith and Terrile (1984) used their "stellar" coronagraph (Vilas & Smith 1987) to uncover a disk-like reflection nebulosity within 1000 AU of β Pic.

Because the lifetime of dust around these nearby main-sequence stars is orders of magnitude shorter than the ages of the central stars, the discoveries pointed to the existence of orbiting exoplanetesimals which replenish the detected grains in the same way that comets and asteroids replenish the Zodiacal disk. The existence of pulsar planets was reported eight years later (Wolszczan & Frail 1992), followed by the discoveries of 17 planets around nearby main sequence stars (Marcy et al. 1999). Thus, by the end of the century, we had determined that nearby stars possess an inventory of objects comparable to that of our solar system (except for terrestrial planets in habitable zones).

3. Observing Replenished Dust Disks

Since IRAS observations of Vega provided the first evidence of replenished grains around a nearby star, the term "Vega Phenomenon" is often used to describe the exosolar analog to our Zodiacal and trans-Neptunian dust system (Backman & Paresce 1993). Stars showing the Vega Phenomenon generate emission at 12, 25, 60 and 100 μm in excess of the expected stellar output. The basic experimental technique selects main sequence stars from stellar catalogs, and cross-correlates their listed positions to the positions of sources in IRAS catalogs, such as the Point Source Catalog. From the spectral types and visible/NIR photometry one then estimates the photospheric spectral energy distribution (SED), and by comparison to the measured SED, determines the level of FIR excess (Fajardo-Acosta et al. 1998). The basic result is the fractional infrared excess, defined as the ratio of far-infrared luminosity to total bolometric luminosity, f=L$_{dust}$/L$_{\star}$. For β Pic, Vega, Fomalhaut, and the Zodiacal light f is equal to 3 x 10^{-3}, 2 x 10^{-5}, 8 x 10^{-5}, and 8 x 10^{-8}, respectively (Backman & Paresce 1993).

Initial studies limited their samples to stars within 25 pc, and perhaps represent the work least likely to suffer errors from source confusion (Kalas 1997). Correcting for selection effects, 10% - 30% of A - K dwarfs display the Vega Phenomenon (this fraction is considered a lower limit; Backman & Gillett 1987, Aumann 1988).

The SED's of Vega-like stars show a deficit of material near the stars (Backman & Paresce 1993). High-resolution imaging in the optical, mid-IR, and sub-mm have confirmed the central holes in the dust distribution. Table 1 summarizes the spatially resolved replenished dust disks.

By "high-resolution" we mean that images now exist that are near diffraction limits. In the optical, HST (2.4 m) WFPC2 and STIS cameras have been used to map β Pic at a resolution of ~0.1-0.2" (FWHM of stellar images; Burrows et al. 1995, Heap et al. 1997). These images confirm a central depleted region and reveal a warp in the disk midplane. In the NIR, the ADONIS AO coronagraph on the ESO 3.6 m maps the inner warp with ~0.12" resolution, and a theoretical simulation supports the existence of a planet inclined by $\sim 3^o$ to the disk midplane (Mouillet et al. 1997a,b). Also in the NIR, HST NICMOS resolves the disk around HR 4796 with ~0.16" resolution (Smith et al. 1998).

In the mid-IR, cameras used on Keck (10 m) image the HR 4796 disk at 10 and 20 microns with ~0.3" (20 AU) and ~0.5" (34 AU) resolution, respectively (Jayawardhana et al. 1998, Koerner et al. 1998). The recent operation of adaptive optics at Keck II promises 0.05" resolution at H, corresponding to a mere 0.16 AU at the distance of ϵ Eri. In the sub-mm (850 μm), SCUBA at the James Clerk Maxwell Telescope (15 m) resolves dust emission around Vega, Fomalhaut, β Pic, and ϵ Eri with 14" resolution (Holland et al. 1998, Greaves et al. 1998).

TABLE 1. Properties of resolved dust disks

Central Star	D(pc)	SpT	Age (yr)	Mass ($M_\odot$)	r_{disk} (AU)	r_{hole} (AU)
Sun	–	G2V	4.6×10^9	10^{-14}	50	30
Beta Pic	19.3	A5V	$1\text{-}3 \times 10^8$	3×10^{-7}	>1300	20
Vega	7.8	A0V	3×10^8	3×10^{-8}	80	26
Fomalhaut*	7.7	A3V	$1\text{-}3 \times 10^8$	5×10^{-8}	150	30
Epsilon Eri	3.2	K2V	$5\text{-}10 \times 10^8$	3×10^{-8}	75	30
HR 4796A*	67.1	A5V	$6\text{-}10 \times 10^6$	$10^{-6} - 10^{-7}$	80	40
55 Cnc*	12.5	G8V	5×10^9	10^{-10}	60	35
BD $+31^o$ 643*	330	B5V	$10^6\text{-}10^7$	$>10^{-6}$	6,600	2300

4. Properties of Replenished Dust Disks

In Table 1, an asterisk after the star name indicates a multiple stellar system. Because gravitational perturbations by a multiple system may retard the settling of gas and dust into a thin, dense disk plane, the naive prediction is that multiple systems are less likely to possess planetesimals and replenished dust disks. Observationally this is not the case - half the replenished disks in Table 1 exist in multiple stellar systems. If planetesimal growth is not hindered by stellar multiplicity, then planet growth may succeed around stellar systems of all types. In fact, about 1/3 of the radial-velocity-detected planetary systems are in multiple stellar systems.

Half the sample in Table 1 consists of early type stars, meaning that there is little overlap in the stellar samples utilized by disk researchers and radial-velocity searches for planets (55 Cnc is the exception). Early type stars are best at illuminating their surroundings, but rotation and a lack of features in the spectra make them non-ideal for radial velocity searches (the cutoff is about F5). One potential obstacle for planet growth around early type stars is the shorter timescale for clearing primordial dust and gas due to enhanced radiation fields - the luminosities of Vega, Fomalhaut and β Pic are 60, 13, and 8.7 $L_\odot$, respectively. The existence of replenished dust disks around these stars indicates that planetesimal and planet growth may be equally successful around early type stars. However, the composition of planetesimals around these stars may be volatile-depleted due to the rapid destruction of ices (Artymowicz 1997).

The ages listed in Table 1 are order-of-magnitude estimates, except for HR 4796A and Fomalhaut where the ages are better constrained by deriving the ages of presumed co-eval, late-type companion stars (Barrado y Navascues et al. 1997; Jura et al. 1998). The dust masses are estimated from sub-mm measurements and *f*. Together, these quantities permit a rudimentary investigation of planetary system evolution. For the solar system, cratering records indicate that that the number of planetesimals raining down on the terrestrial planets decreased by four orders of magnitude over the past 4.5x10^9 yr - roughly as time^{-3} for the first 10^9 yr, and as time^{-1} for the next 3x10^9 yr (Chyba 1990).

For the A stars in Table 1, age estimates indicate that dust mass decreases roughly as time^{-1} for the first 10^9 yr. (Zuckerman & Becklin 1993; Koerner et al. 1998). The discrepancy with the cratering record may arise from different disk evolution rates in and out of planetary growth regions. The dust masses in Table 1 refer to the dustiest part of each system, regions corresponding to our Kuiper Belt, not the terrestrial planet region of our solar system. Thus, a comparison of our early solar system's evolution to that of exosolar disks is hindered by a lack of information about our trans-Neptunian dust complex, and about dust mass in the depleted regions (”holes”) for stars in Table 1.

Table 1 lists a range of ages that shows Fomalhaut, Vega and β Pic could be coeval. Why, then, would the β Pic disk contain one order of magnitude more dust than Fomalhaut and Vega? Whitmire et al. (1992) propose an exogenic process whereby a star passes through an interstellar cloud, temporarily enhancing the erosion of planetesimals. Artymowicz and Clampin (1997) present evidence refuting this idea, and champion the endogenic explanation that β Pic is simply younger. Kalas and Jewitt (1996) invoke both processes - 1000 AU scale asymmetries in the β Pic disk indicate an exogenic perturbation (e.g. a passing star or brown dwarf) that ”stirs” the otherwise quiescent planetesimal system, which is still well-populated due to β Pic’s young age. Another possibility is that disk evolution is dictated by the presence or absence of Jovian-mass planets - the timescale for planetesimal clearing will be significantly longer if a Jupiter-mass planet is missing (Wetherill 1994).

5. What can we learn about exoplanets?

Spectra of the replenished dust disks reveal the composition of the planetesimal parent bodies, which in principle provide the material for building exoplanet cores and modifying their surfaces and atmospheres. A prominent 10 μm emission feature detected in the line of sight to β Pic (Telesco and Knacke 1991), and other Vega-like stars (e.g. Fajardo-Acosta et al. 1993, Sylvester et al. 1996), is attributed to Si-O stretching vibrations in micron-sized silicate particles. More detailed observations and models of β Pic’s silicate feature (Knacke et al. 1994, Li & Greenberg 1998) robustly support the hypothesis of β Pic comets replenishing the short-lived, silicate-rich dust component.

Spectroscopic monitoring also reveals variable, transient, and almost always redshifted lines of neutral and ionized atomic species (reviewed by Lagrange et al. 1999). A model involving families of cometesimals rapidly sublimating in front of β Pic’s photosphere is dynamically viable if the bodies are perturbed from a 4:1 mean motion resonance with a planet (Beust et al. 1996, Beust & Morbidelli 1996).

Images of dust disks constrain the otherwise elusive inclination, i, of the exosolar system to the line of sight (e.g. Fig. 4 of Kalas & Jewitt 1996). Thus, the sin i ambiguity for exoplanetary masses can be solved (e.g. Trilling and Brown 1998). Inclination also shows if a planetary system will eclipse the stellar photosphere. With eclipse data, one can infer the radius of a planet, and, given the mass from radial velocity searches, its density.

Model fits to β Pic give $i \leq 5^o$ (Kalas & Jewitt 1995). Lecavelier et al. (1997) and Lamers et al (1997) discuss a 0.06 magnitude variation of β Pic's light curve, which can be modeled either by an occulting planet, or a dust cloud. Thus, the favorable case of β Pic illustrates the difficulty of assigning unique explanations to any "events" in the light curve of a star, because a dust cloud can produce the same light signature as a planet.

HR 4796A has a more favorable viewing geometry because the disk images show a relatively dust free line of sight through the disk hole to the photosphere. A planetary transit requires tan $i > a / R_*$, where a is the semi-major axis of the planet and R_* the stellar radius. If we take $R_* =$ 1.4 x10^9 m, and $i \sim 75^o$ (Smith et al. 1998), then $a <$ 5 x10^9 m (0.04 AU). Considering that four radial-velocity-detected exoplanets have $a \leq$ 0.05 AU, HR 4796A presents a good opportunity to test for planetary transits.

Observations and modeling of the Zodiacal and Kuiper Belt grains (Dermott et al. 1994, Liou et al. 1996), and β Pic particles (Roques et al. 1994, Mouillet et al. 1997) demonstrate that planets gravitationally modify the structure of a collisionless dust disk. Possible features are central dust depletions, dust concentrations at the orbital radius of a planet, dust rings at mean motion resonances, and vertical warps created when a planet's orbital plane is inclined to that of the disk. Central dust depletions are observationally the most common features, and Table 1 lists their radii as well as the outer disk radii. The models indicate that a hypothetical planet must have $\geq$5 $M_\oplus$ to maintain a dust-free central region (by either ejecting particles outward, or injecting them toward destruction near the star).

If planet formation is a unique explanation for the central holes, then each instance of a central disk cavity would be indirect observational evidence for planet formation. If we estimate the fraction of stars displaying the Vega Phenomenon (F_V), and the fraction of Vega-like stars with central holes (F_h), then to first approximation the fraction of stars that have formed planets is $F_P \sim F_V$ x F_h. The observational evidence suggests $F_V \geq$ 0.1 and $F_h \sim 1$, giving $F_P \geq 10\%$. This is twice the value indicated by radial velocity searches (Marcy et al. 1999). The difference may represent the relative frequencies of terrestrial planet to giant planet formation (e.g. Zuckerman et al. 1995).

Ice sublimation near a star could also contribute in generating a disk hole (e.g. Backman et al. 1992). However, the non-thermal UV photoevaporation of ice grains discussed by Artymowicz (1994, 1997) does not produce a sharp ice boundary. Also, the low luminosities of late-type stars such as ϵ Eri would not cause ice sublimation at the observed hole radii (Table 1). If no other depletion mechanism is proposed, then each instance of a central disk cavity is indirect evidence for planet formation. The hole radii in Table 1 therefore give us the approximate radius of each exosolar system.

6. Conclusions

Given that papers related to the Vega Phenomenon appear in refereed journals at a rate of one per week, this review could not address all the findings of the past 15 years. More comprehensive reviews of physical principles and observations are provided by Backman & Paresce (1993), Lagrange et al. (1999), and Artymowicz (1997).

One theme of the present review is that our understanding of the Vega Phenomenon is incomplete without knowledge gained from the Kuiper Belt, the asteroid belt, the Zodiacal light, and radial velocity searches for planets. Lucid accounts of these topis are provided by Jewitt (1999), Sykes et al. (1989), Leinert and Grün (1990) and Marcy et al. (1999).

Here we briefly reviewed several exosolar dust disks, analogs to our Kuiper Belt, that have been imaged at diffraction-limited resolutions. These images confirm the existence of inner dust cavities previously inferred from the SED's. The cavity radii are comparable to the semi-major axis of Neptune. If the only explanation for the cavities is planet formation, then the observed frequency of the Vega Phenomenon approximates the frequency of planet formation, $F_P \geq 10\%$, and the cavity radii, $r \sim 30$ AU, represent a typical solar system size.

Future work should focus on testing other physical mechanisms that could explain the disk cavities. We also argue for photometric monitoring of HR 4796A, given that its viewing geometry favors planetary transits with relatively little interference from the circumstellar disk. Finally, we recommend increased collaboration between planet search and disk search observing campaigns. This would help test the co-existence and physical relationship between planets, planetesimals, and circumstellar disks.

Acknowledgements: We thank Dana Backman, Pawel Artymowicz and David Jewitt for valuable discussions.

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