THE VEGA DEBRIS DISK:
A SURPRISE FROM SPITZER
Vega Properties

- 25.3 Light away in the constellation Lyra
- Mass 2.6 M☉, Radius 3.1 R☉
- Luminosity 51 L☉
- Metallicity 63%
- Vega is the brightest star in the Lyra, and the fifth brightest star in the sky. It is the second brightest star in the Northern night sky
- Apparent magnitude (V) +0.03
- Absolute magnitude (Mv) 0.58
- Its spectral class is A0V. It is in the main sequence (dwarf)
- Vega's current age is about $3.5 \times 10^8$ years. Its lifetime is only one billion years (white dwarf)
- The flux densities are roughly equal to 2000-4000 Jy. The flux density of Vega drops rapidly in the infrared, and is near 100 Jy at 5 µm
- Vega's polar temperature 9,300 °K , while its equatorial temperature is 7,600 °K
- Vega rotates at 93% of the speed that would cause it to start breaking up from centrifugal effects with a rotation period of about 12.5 hours (sun: 24-30 days)
Dust disk & possible planetary system

- IRAS first discovered infrared radiation excess (1983)
- A circular shell of dust surrounds the star extending outwards to 140 AU
- (Sub-) Millimeter-wavelength observations were sensitive to structures as small as 20 AU
- They managed to resolve two knots in the circumstellar dust that were offset at 60 and 75 AUs from Vega
- The greatest concentration of dust, is centered on a spot located from the star about twice the distance between Pluto and the Sun in the Solar system
If the blob of dust is associated with Vega, it could be a dust cloud around a giant planet orbiting Vega.

The modelling of the asymmetric circumstellar disk infalling into Vega suggests that there may be a planet twice the mass of Jupiter at an orbital distance of about 50 to 60 AU from the star in an eccentric orbit.

The dust would tend to become trapped in the hypothesized planet's mean-motion resonances around Vega.
Numerical Modeling suggests

- The semimajor axis of the planet's orbit may center around 30 AU smaller than 30 times Jupiter's mass.
- The faint dust disk around Vega can be best explained by the presence of Neptune-sized and Jupiter-sized planets orbiting at distances.
- Probably, a Neptune-like planet actually formed much closer to Vega and was pushed by a Jupiter-like planet in an inner orbit out to its current wide orbit around 80 AU away from Vega over about 56 million years, sweeping many comets out with it and causing the dust disk to become clumpy.
However …

- Using Spitzer, the dust disk was found bigger than previously estimated. The disk appears to be mostly composed of small dust particles (1-50 µm) that are probably created by the collision of protoplanetary bodies within approximately 90 AU of the star but are then blown away by its intense radiation.

- On the other hand, the mass and short lifetime of these small particles indicate that the disk detected was created by a large and relatively recent collision that may have involved objects as big as the planet Pluto.
In this Paper (Su et al.)

- High spatial resolution mid- and far-infrared images of Vega debris disk with MIPS were used.
- The disk is well resolved, and its angular is much larger than previously found. 330, 543, 815 AU at 24, 70 and 160 µm!!
- Circular, Smooth, and without clumpiness at all three wavelength, power law radial surface brightness profile.
- Radial surface brightness profiles follow radial power laws of $r^{-3}$ or $r^{-4}$ and imply an inner boundary at a radius of $11'' \pm 2''$ (86 AU). Surface number density falls like $1/r$.
- Axially symmetric disk of $(3.0 \pm 1.5) \times 10^{-3}$ Mearth.
Radial Profile of Vega

- The Vega disk at 24 m is tenuous compared to the very bright photosphere (7.4 Jy).
- The existence of a very low surface brightness disk is best illustrated by examining the radial profile.
- Relative to the observed point-spread function (PSF) scaled to Vega’s photospheric level, the observed radial profile lies consistently above the scaled point-source profile.
- Vega’s photosphere contributes a significant fraction of the flux near the center of our images at both 24 and 70 µm.
- Vega’s debris disk dominates most of the flux at 160 µm.

![Graph showing radial profile of Vega (photosphere + disk) at 24 µm after background subtraction. For comparison, the radial profile of an observed point source is scaled to Vega’s photosphere flux (filled circles). The observed radial profile lies consistently above the point-source profile. The contrast between the bright and dark Airy rings in the PSF signatures is not as prominent as the one in the point source, suggesting the existence of a tenuous disk. [See the electronic edition of the Journal for a color version of this figure.]
Disk Morphologies at 24, 70 & 160 µm

- The disk at 24 µm is symmetric and centered at the star position, ~32 (330 AU) in radius 1.5 Jy(±10%), in agreement with IRAS 25 µm
- Similarly in 70 µm, no obvious clumpy structure in the fine-scale image. ~70” (543 AU) in radius. Total flux~7 Jy (±20%)
- Assuming azimuthal symmetry, at 160 µm, the outermost of the disk ~105” (815 AU), ~4Jy (±20%)
- The disk is circular at all wavelengths, suggesting a face-on disk
- SED of the disk can be characterized as a blackbody of T=95K
- Surprise 1: Submillimeter and millimeter ~11” radius, (Fomalhaut debris disk had an agreement between Submillimeter & IR)
- Surprise 2: Presence of material warm enough to be detected at large distance
The Surface Brightness Radial Distribution

Radial profile of Vega at 24 µm, Best fit-power law index is -4.1±0.1
Radial profile of Vega at 70 µm, Best fit-power law index is -3.8±0.1
Conclusion: the disk surface brightness distribution follows simple power-law dependencies, implying that the disk density structure is simple and smooth.
Radial Profile for 24 & 70 µm for different power law profile models

Fig. 6.—Radial profile of the Vega disk at 24 µm (open circles) compared with modeled surface brightness distributions after convolution with the instrumental beam. Note that the background value determined in Fig. 5 has been added back into the fits. The model fit with a steep power law (−4 or −3) and no inner boundary of the disk is shown as a green solid line, which resembles a PSI. The other models are model A, an empty hole with $r^{-4}$ (solid red line); model B, an empty hole with $r^{-1}$ (solid blue line); model A', a flat distribution with $r^{-4}$ (dashed red line); and model B', a flat distribution with $r^{-1}$ (dashed blue line). Bottom: Ratios between the modeled and observed radial profiles.

Fig. 8.—Radial profile of the Vega disk at 70 µm compared with model surface brightness distributions after convolution with the instrumental beam. Similar to Fig. 6, the background value has been added back into the model fits. Symbols and color scheme are the same as in Fig. 6. Bottom: Ratios between the modeled and observed radial profiles.
Radial Profile for 160 µm

Fig. 10.—Radial profile of the Vega disk at 160 µm compared with model surface brightness distributions after convolution with the instrumental beam. The background value is not included in the fits. Symbols and color scheme are the same as Figs. 6 and 8. Bottom: Ratios between the modeled and observed radial profiles.

Fig. 9.—Radial-dependent [24] – [70] distribution for the Vega disk. The observed color is plotted as filled squares. The color based on the canonical dust temperature is plotted as open diamonds, compared to the ones derived from single-sized silicates (a = 5.1 µm, solid line and a = 2 µm, dashed line). The [24] – [70] color derived from our two-component model (see § 5.1) is also plotted (dot-dashed line). [See the electronic edition of the Journal for a color version of this figure.]
So,

- A radial-dependent power law with index of -3 (inner part) or -4 (outer part)
- The radial power law dependence can’t apply all the way to the star, a hole or a flat distribution is required
  - The hole: a region lacking material that emits strongly at 24, 70 and 160 µm
  - The radius of the hole is \( \sim 11'' \pm 2'' \) about the same size as the 850 µm ring.
- So Maybe, the MIPS bands originate from the submillimeter ring where collisions generate small debris blown away by radiation.
Disk Structure and Mass

Fig. 11.—Thermal equilibrium temperature distribution for different grains in the Vega environment. Astronomical silicates are plotted as black solid and dash-dotted lines, and amorphous carbon grains are plotted as gray solid and dash-dotted lines. [See the electronic edition of the journal for a color version of this figure.]

Fig. 16.—Three-component model fit with small (2 μm) and large (18 μm) grains in the disk and very large grains (215 μm) in the ring. The symbols and lines are the same as in Fig. 12, with colors indicating wavelengths: 24 μm, blue; 70 μm, green; 160 μm, red; and 850 μm, purple. The model emission from the 215 μm grains in the ring is plotted as dotted open squares, with color representing different wavelengths. The solid lines are the total model emission from the three-component model.
Fig. 12.—Observed radial surface brightness profiles for the Vega debris disk are plotted as open circles, with colors representing different bands (24 μm, blue; 70 μm, green; and 160 μm, red). Model profiles from the large grain \(a = 18 \mu m\) component and the small grain \(a = 2 \mu m\) component are plotted as dashed lines and dash-dotted lines, respectively, with colors indicating the different bands. The sum of the two components is plotted as solid lines, with colors representing the different bands. The 850 μm emission from the two-component grain model is also plotted (purple solid line) for comparison to data from JCMT/SCUBA (purple open circles).

Fig. 13.—Similar to Fig. 12, but using the model profiles from a grain size distribution, \(n(a) \propto a^{-3}\), with a minimum size cutoff \(a_{\text{min}} = 1.0 \mu m\) and maximum size cutoff \(a_{\text{max}} = 46 \mu m\). The symbols and lines are the same as in Fig. 12.

Fig. 14.—Same as Fig. 13, but using amorphous carbon grains instead of silicates. At the MIPS wavelengths, the modeled profiles are very similar to the ones using silicate grains due to the similar temperature distributions and emission efficiency. However, for a particle with \(a = 2 \mu m\), the emission efficiency \(\epsilon_{\text{em}}\) at 850 μm for amorphous carbon grains is twice as large as the one for silicates. As a result, the modeled emission at 850 μm using amorphous grains is much brighter and more extended compared to the emission using silicates.

Fig. 15.—Same as Figs. 13 and 14, but using a mixture of amorphous carbon (30%) and silicate grains (70%). The emission from amorphous carbon grains is plotted as dashed lines, while the emission from silicate grains is plotted as dash-dotted lines. The best-fit grain size distribution is \(n(a) \propto a^{-3}\), with a minimum size cutoff \(a_{\text{min}} \sim 3.2 \mu m\) and maximum size cutoff \(a_{\text{max}} \sim 29 \mu m\).
Disk Structure and Mass

- A range of models using amorphous silicate and/or carbon grains of sizes from ~1 to 50 µm can fit the infrared radiometric behavior of the disk out to ~800 AU.
- Grain size limits depend on the adopted grain composition.
- All these models require an 1/r surface number density and a total mass of $(3.0\pm1.5) \times 10^{-3} \, M_{\text{Earth}}$ in grain.
- Models that fit the submillimeter data additionally require an inner ring (~100 AU) with larger grains (>180 µm) and a total mass > $10^{-3} \, M_{\text{Earth}}$. 


Origin of the Debris

- One possibility: The dust seen at 100–800 AU is produced from a highly extended Kuiper Belt around Vega. This gives a 100 M_earth kuiper belt!, and non smoothness.
- Another possibility is interstellar medium. Radial symmetry strongly suggest that the star itself is the source of the dust NOT interstellar medium.
- From Comet?
  - Large extent and the radial and azimuthal distributions of Vega’s disk are all consistent with a model in which dust at ~100 AU is blown away by radiation pressure.
  - Grain sizes (~1-50µm) deduced from this model are consistent with being pushed out by radiation pressure: small grains are ejected (at a time small of one orbital period ~1000 year), large grains spiral in under the influence of Poynting-Robertson drag.
  - Inner ring seen at submillimeter (86-200AU) imply very long residence.
  - Taking the dust mass in small grains to be ~3.0 10^-3 M_earth and ~1000 year residence, the required dust production rate is ~6 10^14 g/s (~2 10^8 for Hale-Bopp comet). So, the source is not Comet!

- Also, the disk can’t be originated when Vega was born (0.3-3 M_solar of the disk is large).
- This suggest the disk is ephemeral! They favor a scenario of collisional cascade subsequent to a large disruptive collision of pluto size planets!
References