Direct Detection of a Resolved K-Band Emission in the Inner Vega System

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I. Abstract

Vega, one of the prototypic debris-disk stars, is known to be surrounded by a cold circumstellar disk similar to the Solar Kuiper Belt, located at about 80 AU from the star (Holland *et al.* 1998). This disk has recently been imaged by Spitzer (Su *et al.* 2005), showing very extended emission which suggests recent major collisions between small bodies and subsequent blow-out of small particles by radiation pressure.

Small amounts of warm dust are also expected to be found in the inner "planetary" region. However, the need for high contrast, high angular resolution imaging has prevented investigation until now. In this poster, we give a new insight on the close neighborhood of Vega with the help of infrared stellar interferometry (CHARA/FLUOR) and **estimate the *K*-band excess that originates from the central 8 AU of the debris disk: 1.22 ± 0.16%**. We show that our result is consistent with previous studies, and derive some constraints on the physics of the inner disk.

II. Observations

We performed precise visibility measurements at both short (S1-S2 = 34m) and long (E2-W2 = 150m) baselines with the **FLUOR** beam-combiner installed at the **CHARA Array** (Mt Wilson, California). The **field-of-view** of the instrument is 1 arcsec in radius (**~8 AU** at the distance of Vega), so that our measurements are only sensitive to the close neighborhood of Vega. The data obtained at long baselines allow us to determine the angular diameter of the stellar photosphere with a good precision: $\theta_{UD} = 3.203 \pm 0.003$ mas (Fig. 1).

However, a comparison of the best-fit UD model with the **short-baseline** data shows that the model is significantly above the measurements, by $\Delta V^2 \sim 2\%$. This **deficit of visibility** with respect to the stellar UD model suggests the presence of an additional source of emission close to Vega, resolved with the S1-S2 baseline ("incoherent emission"). For instance, the addition of a diffuse emission uniformly spread on the CHARA/FLUOR field-of-view and representing 1.22% of Vega's photospheric flux reconciles the model with the observations (Fig. 2).

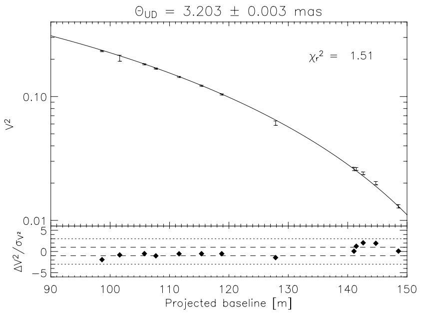

Fig. 1 Fit of a uniform stellar disk (UD) model to the data obtained at long baselines (E2-W2: 150m) with CHARA/FLUOR.

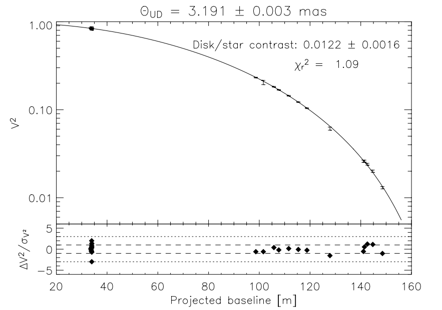

Fig. 3 Fit of a uniform stellar disk + circumstellar disk model to our full data set (short and long baselines), using the model of Kelsall *et al.* 1998.

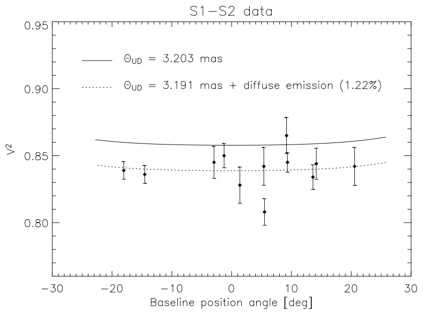

Fig. 2 The points obtained with the S1-S2 baseline (34m) are displayed as a function of the projected baseline's position angle together with the best UD fit computed on the whole data set (3.203 mas). The data points are significantly below the best UD fit, with a **visibility deficit $\Delta V^2 \sim 2\%$**. The addition of a diffuse source of emission in the FLUOR field-of-view reconciles the best fit with the data (dotted line).

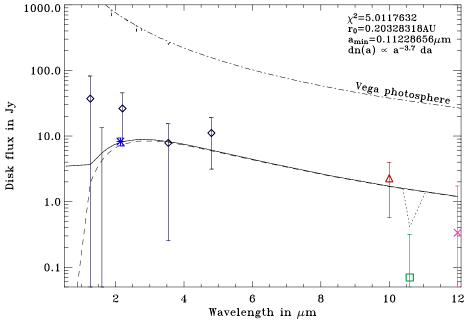

Fig. 4 The model of Augereau *et al.* (1999) can reproduce the photometric and interferometric constraints on the inner disk at various wavelengths. Solid line: total emission of the inner disk; dotted line: includes spatial filtering from the interferometric studies; dashed line: thermal emission only. Diamonds: Campins *et al.* (1985). Triangle: Rieke *et al.* (1985). Cross: Cohen *et al.* (1992). Square: Liu *et al.* (2004). **Blue asterisk: this study (by far the most constraining)**.

III. Possible sources for the observed visibility deficit

- *Calibration* : We have used six different **calibrator stars** from the catalogue of Mérand *et al.* (2005) to measure the instrumental response of the FLUOR beam-combiner. In order to explain the observed visibility deficit, the diameters of the three calibrators used for the S1-S2 baseline should have been underestimated by more than 10% with respect to the calibrators used for E2-W2, which is very unlikely as their diameters are known with a typical precision of 1%.
- *Instrument* : As the FLUOR instrument provides a stable and well-characterized instrumental response, and as it corrects for flux imbalances between the two interferometric arms through simultaneous photometric measurements, we do not expect the instrument itself to induce any bias between the short and long baseline observations.
- *Stellar morphology* : A **limb-darkened** stellar model will not reconcile the best fit stellar model with the S1-S2 data points because low spatial frequencies are not sensitive to limb darkening. Stellar **asymmetry** could be a possible reason for the visibility deficit at short baselines, because the S1-S2 and E2-W2 baselines are almost perpendicular. However, an oblateness ratio of 1.07 would be needed to explain the deficit, which would strongly contradict previous interferometric studies (van Belle *et al.* 2001, Peterson *et al.* 2004). Other stellar features such as **spots** would not explain this deficit either as they can only appear in the second lobe of the visibility function and above.
- *Circumstellar material* : The thermal and scattered emissions from the debris disk surrounding Vega would be a natural explanation to the visibility deficit observed at short baselines, provided that a sufficient quantity of dust is present close to the star. In order to assess the adequacy of a circumstellar disk to reproduce the data, we have fitted the **zodiacal disk model** of Kelsall *et al.* (1998) to our full data set, assuming that the inner dust distribution around Vega follows the same power-law as the Solar zodiacal cloud. The result is displayed in Fig. 3: all data points are nicely spread around the best-fit model. The resulting **flux ratio** between the inner circumstellar disk and the stellar photosphere (**1.22 ± 0.16%**) is the same as with a simple model of uniform diffuse emission, indicating that the interferometric data are not sensitive to the particular morphology of the incoherent emission (this is due to our sparse sampling of the spatial frequency plane). Using the model of Kelsall *et al.* (1998), a flux ratio of 1.22% in *K* band would suggest that the dust **density level** in the inner Vega system is about **3000 times larger than around the Sun**.
- *Binarity* : A binary star model with a flux ratio of 1.22% between Vega and its companion could also reproduce the observations. Assuming the companion to be a dwarf star with the same age as Vega (~350 Myr), the evolutionary models of Baraffe *et al.* (1998) suggest an effective temperature of 3890 K and a mass of 0.60 $M_\odot$, which corresponds to an **M0V** type. This companion would not have been detected by adaptive optics studies due to the very small angular separation. However, astrometric measurements with *Hipparcos* give a strong constraint on the orbital solution for the putative companion: the **semi-major axis of the binary system must be smaller than 0.05 AU** (= 4 R_*) in order to explain the astrometric stability of Vega (1.5 mas at 3σ). Such a small separation is **incompatible with the measured radial velocity stability** of Vega of 100 m/s (F. Galland, private communication) assuming that the orbital plane of the system is perpendicular to Vega's rotation axis (inclined by 5.1° with respect to the line-of-sight). In order to explain the RV stability, the orbital plane should coincide with the plane of the sky to within 0.13°. Such a configuration has a very low probability (less than 10^{-3}). The presence of a field star is also highly unlikely as the local density of objects with *K*<5 is about 4 × 10^{-7} per arcsec^2 according to the 2MASS survey.

IV. Discussion and conclusions

The above discussion suggests a **diffuse circumstellar emission** as the most probable explanation for the observed visibility deficit at small baselines. In order to assess the adequacy of a realistic circumstellar disk model to reproduce the photometric constraints from various studies, we have used the model developed by Augereau *et al.* (1999) with various dust compositions, grain size distributions and density power-laws. The (non-unique) result of the fit is displayed in Fig. 4. The interferometric data (blue and green) are the most constraining, and lead to the following **preliminary physical characteristics**:

- large amount of dust in the Vega inner system (~10^{-7} $M_\oplus$);
- **large bolometric luminosity ratio** for the inner disk ($L_{disk}/L_* \sim 4 \times 10^{-3}$);
- **mostly small grains** ($a_{min} \sim 0.1$ µm with steep size distribution ~ $a^{-3.7}$), which are hot and mostly emit in the near-IR;
- **small lifetime** for these grains (~1 yr), suggesting continuous replenishment;
- large amounts of **refractive grains** (e.g. amorphous carbon), which are hotter than silicates and do not show an important emission around 10µm;
- small inner radius (~0.2 AU) for the inner disk (note that small grains ~0.1 µm in diameter are more subject to sublimation than larger grains and cannot survive closer than ~0.5 AU);
- steep surface density power-law (r^{-4} or steeper).

Such a significant dust density in the Vega inner system, combined with the suspected collisional activity in the outer ring (Su *et al.* 2005), could be related to a **major dynamical event** ongoing in the Vega system, e.g. an equivalent to the solar system Late Heavy Bombardment, which was most probably triggered by the migration of the outer planets.