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# Hot circumstellar material around Vega

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**RÉSUMÉ.** Des mesures de visibilité très précises ont été obtenues sur Vega, un des prototypes d'étoiles à disque de débris, avec l'interféromètre FLUOR installé sur le réseau CHARA. La combinaison de lignes de base longues et courtes nous a permis de résoudre séparément la photosphère stellaire et son environnement proche ( $< 8$  UA). Un déficit de visibilité significatif est observé à courte base, suggérant la présence d'une source d'émission étendue. La présence de poussières chaudes situées dans la partie interne du disque de débris de Vega semble la source la plus probable pour cette émission circumstellaire. Un rapport de flux de  $1.29 \pm 0.19\%$  est déduit de nos observations. Cette information, complémentée par des mesures photométriques d'archive, nous permet d'étudier les propriétés physiques des grains de poussière. Nos simulations suggèrent que d'importants phénomènes dynamiques pourraient actuellement être en train de perturber le système planétaire de Vega.

**ABSTRACT.** Using the FLUOR beam-combiner at the CHARA Array, we have obtained high-precision visibility measurements of Vega, a prototypic debris-disk star. The combination of long and short baselines has allowed us to separately resolve the stellar photosphere and the close environment of the star ( $< 8$  AU). Our observations show a significant deficit in square visibility at short baselines with respect to the expected visibility of a simple uniform disk stellar model, suggesting the presence of an extended source around Vega. We propose that the excess emission is most likely due to the presence of hot circumstellar dust in the inner part of Vega's debris disk, with a flux ratio of  $1.29 \pm 0.19\%$  between the integrated dust emission and the stellar photosphere. Using this information together with archival photometric measurements in the near- and mid-infrared, we derive the expected physical properties of the circumstellar dust by modelling its infrared Spectral Energy Distribution. The inferred properties suggest that the Vega system could be currently undergoing major dynamical perturbations.

**MOTS-CLÉS :** Étoiles: individu: Vega, Matière circumstellaire, Techniques: interférométrie.

**KEYWORDS:** Stars: individual: Vega, Circumstellar matter, Techniques: interferometric.

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## 1. Introduction

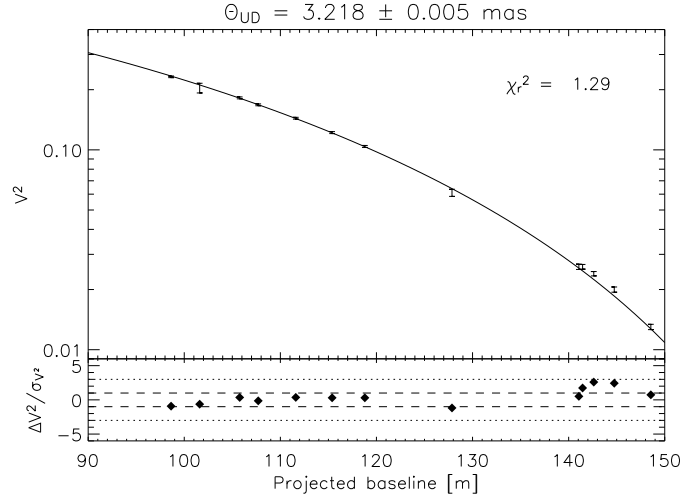
More than 20 years ago, the bright star Vega (HD 172167, A0V, 7.76 pc) was shown to have a large infrared excess beyond  $12\ \mu\text{m}$  with respect to its expected photospheric flux (Aumann *et al.*, 1984). This excess was identified as the thermal emission from a circumstellar disk of cool dust located at about 85 AU from Vega. Since then, great attention has been paid to Vega and other Vega-like stars. They have been imaged from the millimetric domain down to the visible, revealing for instance a smooth annular structure around Vega, similar to the solar Kuiper Belt and containing about  $3 \times 10^{-3} M_{\oplus}$  of dust grains (Holland *et al.*, 1998).

However, due to the limitations in angular resolution and in dynamic range of single telescopes, very little is known about the innermost part of these debris disks, which could potentially harbour warm dust ( $\geq 300\ \text{K}$ ) heated by the star. In this paper, we use infrared stellar interferometry to investigate the inner part of Vega's debris disk. Such an attempt had already been made at PTI (Ciardi *et al.*, 2001), using a 110 m long baseline in dispersed mode. However, the poor spatial frequency coverage of these observations did not allow clear conclusions, although a simple model of a star and a uniform dust disk with a 3 – 6% flux ratio was proposed to explain the observations. In order to better constrain the near-infrared brightness of Vega's disk, we have used a combination of short and long baselines at the CHARA Array in order to separately resolve the two components of the system (stellar photosphere at long baselines and circumstellar emission at short baselines).

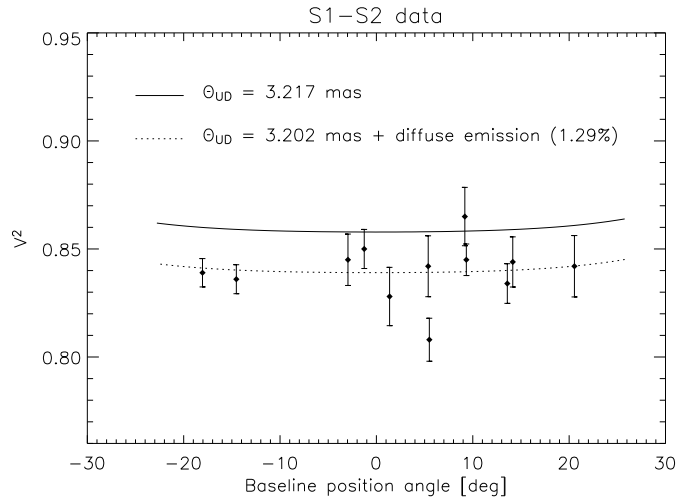
## 2. Observation and data analysis

Interferometric observations were obtained in the infrared  $K$  band ( $1.94 - 2.34\ \mu\text{m}$ ) with FLUOR, the Fiber Linked Unit for Optical Recombination, using the S1–S2 and E2–W2 baselines of the CHARA Array, 34 and 156 metres respectively. A full description of the data set and details on the data reduction procedure can be found elsewhere (Absil *et al.*, 2006). The measurements obtained with the E2–W2 baseline are particularly appropriate for a precise diameter determination, because they provide good spatial frequency coverage of the end of the first lobe of the visibility curve. We have fitted a uniform stellar disk model to our E2–W2 data, assuming that Vega's photospheric intensity  $I(\phi, \lambda)$  equals the Planck function with an effective temperature of 9550 K for all angles  $\phi$  (Figure 1). The best-fit diameter is  $\theta_{\text{UD}} = 3.218 \pm 0.005\ \text{mas}$  for an effective wavelength of  $2.118\ \mu\text{m}$ .

With this precise diameter estimation, we can now have a look at the short-baseline data. In fact, these points do not significantly contribute to the UD fit because of the low spatial frequencies they sample. Including all the data points in the fitting procedure gives a best-fit diameter  $\theta_{\text{UD}} = 3.217 \pm 0.013\ \text{mas}$ , but with a poor  $\chi_r^2 = 3.36$ . We show the reason for this poor reduced  $\chi^2$  in Figure 2, where the S1–S2 data points are plotted as a function of the projected baseline's orientation together with the best UD fit (solid line) : the observations are consistently below the fit.



**Figure 1.** Fit of a uniform stellar disk model to the E2–W2 data. The quality of the fit is quite good, with small residuals that do not display any obvious trend.



**Figure 2.** Squared visibilities obtained with the S1–S2 baseline, plotted as a function of the projected baseline's position angle. The data points are significantly below the best UD fit of 3.217 mas (solid line), with a mean visibility deficit  $\Delta V^2 = 1.88 \pm 0.34\%$ . The addition of a uniform diffuse source of emission in the FLUOR field-of-view reconciles the best fit with the data (dotted line).

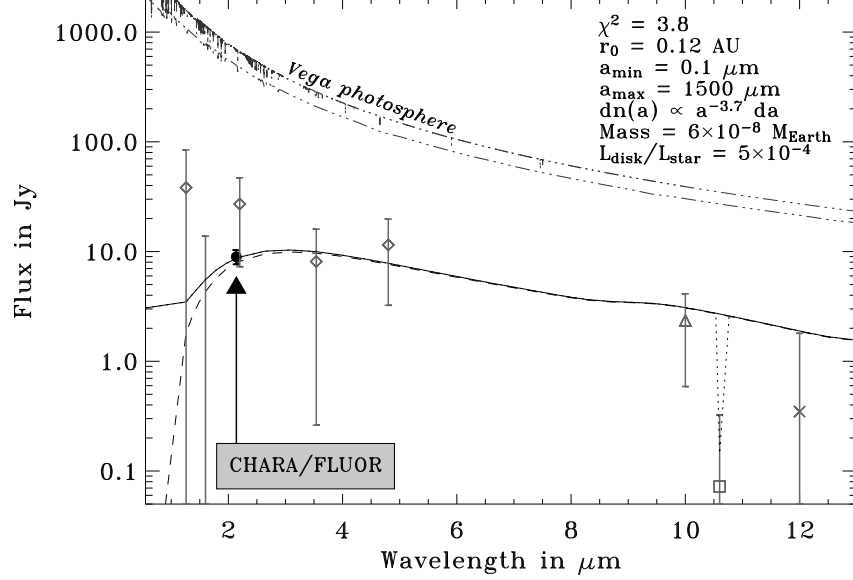
A limb-darkened stellar model for Vega will not reconcile the best-fit stellar model with the S1–S2 data points, because low spatial frequencies are not sensitive to limb darkening. Stellar oblateness cannot be an explanation either, as Vega is seen pole-on (Aufdenberg *et al.*, 2006). A natural explanation to the observed visibility deficit would be the presence of an extended source of emission in the interferometric field-of-view (e.g. disk or companion), which would be resolved with the S1–S2 baseline (i.e., incoherent emission). In order to assess the amount of incoherent emission needed to explain the observed visibility deficit, we have added a diffuse infrared source, uniformly distributed in the CHARA/FLUOR field-of-view, to our UD stellar model. Fitting this new model to the complete data set gives the following final result :  $\theta_{\text{UD}} = 3.202 \pm 0.005$  mas,  $K$ -band flux ratio =  $1.29 \pm 0.19\%$ , with a significantly decreased  $\chi_r^2 = 1.10$  (instead of 3.36). This result is almost independent of the extended source morphology, as the spatial frequency coverage of our interferometric data is too scarce to constrain its spatial distribution.

### 3. Discussion

The presence of a point source located within the FLUOR field-of-view ( $1''$ ) could possibly explain our observations. However, based on the available astrometric and radial velocity data, the presence of a stellar (or sub-stellar) companion within the field-of-view seems very unlikely (Absil *et al.*, 2006). Therefore, we suggest that the circumstellar emission arises from the inner part of Vega’s debris disk, where warm dust grains can produce a significant near-infrared flux.

Based on our estimation of the  $K$ -band contrast between the star and the disk ( $1.29 \pm 0.19\%$ ), we have evaluated the main physical properties of the dust grains in the inner debris disk. To that purpose, we have complemented our  $K$ -band data with the photometric constraints on the near- and mid-infrared excess flux around Vega currently available in the literature (Absil *et al.*, 2006). These measurements have larger error bars (typically about 3%), so that they are far less constraining than our interferometric measurement. Photometric constraints at wavelengths longer than  $12 \mu\text{m}$  are not appropriate for our purpose as they are mostly sensitive to the cold outer disk. We have tried to reproduce the Spectral Energy Distribution (SED) of the infrared excess with the debris disk model of (Augereau *et al.*, 1999). For that purpose, we have taken for Vega the photospheric model proposed by (Aufdenberg *et al.*, 2006) and we have assumed that the plane of the circumstellar disk coincides with the equatorial plane of Vega (Figure 3). The main outcome of our simulations can be summarised as follows.

The inner disk seems to be mainly composed of hot ( $\sim 1500$  K) and small ( $< 1 \mu\text{m}$ ) dust grains, which emit mostly in the near-infrared. This suggests a steep size distribution with a small minimum grain size ( $a_{\text{min}} \leq 0.5 \mu\text{m}$ , assuming compact grains). For instance, we find that a size distribution similar to that of cometary grains provides a good fit to the SED, as well as the interstellar size distribution (Reach *et al.*, 2003). Large amounts of highly refractive grains, such as graphites or amorphous carbons, are



**Figure 3.** A possible fit of our debris disk model to the photometric and interferometric constraints in the near- and mid-infrared. The model used here has a size distribution  $dn(a) \propto a^{-3.7} da$  with limiting grain sizes  $a_{\min} = 0.1 \mu\text{m}$  and  $a_{\max} = 1500 \mu\text{m}$ , a surface density power-law  $\Sigma(r) \propto r^{-4}$  with an inner radius  $r_0 = 0.12 \text{ AU}$ , and assumes a disk composed of 50% amorphous carbon and 50% glassy olivine. The solid and dotted lines represent the total emission from the disk on a 8 AU field-of-view, respectively without and with the spatial filtering of interferometric studies, while the dashed line takes only the thermal emission into account. The pole-on and equatorial photospheric SEDs from Aufdenberg et al. (2006) are represented as a dashed-dotted lines for comparison (the upper curve is the pole-on SED). The pole-on luminosity, which is twice larger than the equatorial luminosity, has been used to compute the apparent luminosity ratio between the disk and the star ( $L_{\text{disk}}/L_{\star}$ ). The actual luminosity ratio, which represents the capacity of the debris disk to reprocess the stellar light, is in fact a factor two larger as it should be computed with the equatorial luminosity (seen by the disk).

most probably present in the inner disk. This is required in order to explain the lack of significant silicate emission features around  $10 \mu\text{m}$ , which are especially prominent for small grains. Silicate grains can still be present in the disk, but with a maximum volume ratio of  $\sim 70\%$ . The inner radius  $r_0$  of the dusty disk is estimated to be between 0.12 and 0.2 AU. A steep power-law for the radial surface density distribution has also been inferred from our investigations. All these properties make the Vega inner disk very different from the zodiacal dust disk around our Sun, which is composed of lar-

ger, mostly silicate grains (Reach *et al.*, 2003), and has a rather flat surface density power-law. The estimated mass of the dust disk in the first 8 AU around Vega is quite small ( $M_{\text{dust}} \sim 6 \times 10^{-8} M_{\oplus}$ ), but the associated bolometric luminosity ratio is still significant ( $L_{\text{disk}}/L_{\star} \sim 5 \times 10^{-4}$ ) due to the high temperature of the grains.

Due to radiation pressure, small grains will not survive in the Vega inner disk more than a few years before being ejected toward cooler regions. A large dust production rate ( $\sim 10^{-8} M_{\oplus}/\text{yr}$ ) is thus needed to explain our observations, suggesting that major dynamical perturbations are currently ongoing in the Vega system. An attractive scenario would be an equivalent to the Late Heavy Bombardment that happened in the solar system in the 700 Myr following the formation of the planets, i.e., at a period compatible with the age of Vega ( $\sim 350$  Myr). Such a bombardment, most probably triggered by the outward migration of giant planets, could explain the presence of small grains around Vega both in its outer disk, due to an enhanced collision rate in this part of the disk, and in its inner disk, due to the high number of comets sent toward the star by gravitational interaction with the migrating planets.

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