# Studying hot exozodiacal dust with near-infrared interferometry

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## ABSTRACT

Since our first detection of a resolved near-infrared emission around the main sequence star Vega, which we identified as the signature of hot dust grains close to the sublimation limit, we have been systematically searching for similar signatures around a magnitude-limited sample of nearby main sequence stars with the FLUOR instrument at the CHARA array. About 40 targets with spectral types ranging from A to K have been observed within the last 6 years, leading to first statistical trends on the occurence of the bright exozodi phenomenon as a function of spectral type. Our target sample is balanced between stars known to harbour cold dust populations from space-based missions (e.g., Spitzer, Herschel) and stars without cold dust, so that the occurence of abundant hot dust can also be correlated with the presence of large reservoirs of cold planetesimals. In this paper, we present preliminary conclusions from the CHARA/FLUOR survey. We also discuss the first results obtained in 2011/2012 with the new PIONIER visiting instrument at the VLTI, which is now used to extend our survey sample to the Southern hemisphere and to fainter targets. A first measurement of the exozodi/star flux ratio as a function of wavelength within the H band is presented, thanks to the low spectral resolution capability of PIONIER. Finally, we also briefly discuss our plans for extending the survey to fainter targets in the Northern hemisphere with an upgraded version of the FLUOR beam combiner.

**Keywords:** Circumstellar matter, planetary systems, interferometry

## 1. INTRODUCTION

Similarly to the zodiacal dust in our solar system, exozodiacal dust is expected to be ubiquitous in mature extrasolar planetary systems. This second-generation dust population is mainly produced by the evaporation of comets and the collision of larger rocky bodies (e.g., asteroids, planetesimals). By producing a significant amount of thermal emission and scattered light, this dust is expected to be one of the major hurdles in the direct detection of Earth-like planets by future high-contrast imaging instruments. Yet, exozodiacal disks are also considered as valuable signposts for the presence of (terrestrial) planets in inner planetary systems (including the habitable zone), since the footprint of planets generally appears as inhomogeneities (clumps, warps, gaps, etc.) in the dusty disks to due gravitational interactions. There is therefore a major scientific interest in studying exozodiacal disks.

The detection and characterization of exozodiacal disks by classical spectro-photometry is a very difficult task, because the spectral energy distribution of warm dusty disks peaks in a wavelength range where the stellar flux is high. Spectro-photometric detections of dust emission at wavelengths shorter than $\sim 20\mu$m are indeed rare (e.g.,[1]). A more appropriate way to study exozodiacal dust would be to resolve the disk from its host star using high-angular resolution observing techniques. In particular, infrared long-baseline interferometry has the

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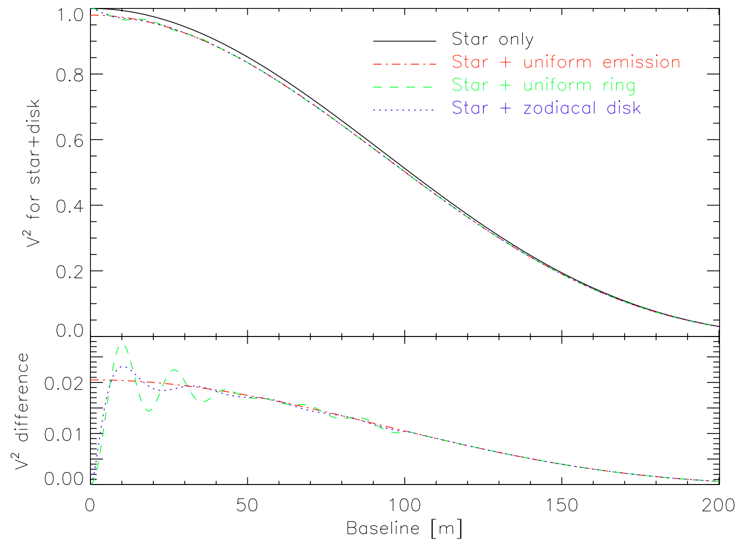


Figure 1. Illustration of the exozodi detection principle with infrared interferometry, for an A-type star at 10 pc with a 1% disk/star flux ratio. The disk creates a small drop in the observed $V^2$ relative to the expected stellar $V^2$. The uniform emission model is generally a good approximation for more realistic exozodical disk models. The exozodi detection is most easily performed at short baselines, where the $V^2$ difference is the largest, and where the influence of the stellar model is the smallest ($V_*^2 \simeq 1$).

potential to resolve exozodiacal disks, which are expected to appear at angular distances typically ranging from 30 to 100 mas around nearby ($\sim 10-20$ pc) main-sequence stars. Such disks would indeed be fully resolved at baselines longer than about 20 m in the K band, and thereby produce a drop in the observed visibility relative to the expected visibility of the stellar photosphere[2–6] (see Figure 1).

Following this methodology, we have observed in 2005 the bright star Vega with the CHARA/FLUOR high-precision infrared interferometer, working at K band.[2] The measured squared visibilities ($V^2$) show a small but significant drop of $1.29\% \pm 0.27\%$ at short baselines compared to the expected photospheric $V^2$. This is the direct indication of resolved circumstellar emission, which we interpret as the signature of hot dust around Vega. Further observations with IOTA/IONIC at H band[7] allowed us to constrain the nature of the dust grains with radiative transfer modelling, suggesting that the grains are very small ($< 1\mu$m), located close to their sublimation distance (around 0.2-0.5 AU depending on the grain size), with temperatures up to 1700 K for carbonaceous grains. These grains are not supposed to survive more than a few years at this location due to radiation pressure and collisions, which points either towards an isolated catastrophic event or towards an inordinate replenishment rate.

## 2. THE CHARA/FLUOR EXOZODI SURVEY

In order to assess whether the "hot exozodi" phenomenon discovered around Vega is frequent around other stars, we initiated a small survey of main sequence stars using CHARA/FLUOR at short baselines.

### 2.1 A magnitude-limited sample

Our sample was defined with two main goals in mind: (i) explore the dependence of the hot exozodi phenomenon as a function of spectral type, and (ii) investigate its correlation with the presence of large reservoirs of cold dust in outer planetary systems around the target stars. We have therefore considered all the debris disk stars (i.e., stars with cold dust detected in the far-infrared) with a K-band magnitude below the magnitude limit of $K < 4$ for high-precision FLUOR observations, resulting in about 25 stars at the time our sample was defined. We tried to balance our sample between three spectral type categories (A, F and G-K), which was actually already almost the case. Finally, we have selected a similar amount of main sequence stars that are not know to harbour any cold dust, to be used as a comparison sample. This non-dusty sample has also been chosen evenly between the three defined spectral classes (A, F and G-K), and with similar magnitudes as the dusty sample in order to reduce possible observing biases. The selected stars are generally main-sequence stars (luminosity class V), although some of them are sub-dwarfs (luminosity class IV).

Our detection methodology requires the stellar diameters to be well known, so that the photospheric $V^2$ can be predicted with a sufficient accuracy at short baselines. Because the stellar photospheres are generally mostly unresolved at the short baselines used here, we can generally rely on surface-brightness relationships[8] to predict stellar angular diameters. Special care was taken to use accurate infrared photometry in these estimations, which is generally not the case of 2MASS magnitudes (saturated for stars with $K < 4$).

## 2.2 Observations and data reduction

Observations were performed on the short S1-S2 baseline ($\sim 34$ m) of the CHARA array using the FLUOR beam combiner between 2005 and 2011. A total of 42 stars were observed, in addition to Vega. The observations of 8 of these 42 stars have already been reported in previous papers.[3,4] The observations of our scientific targets were interleaved with observations of calibrator stars, mostly K giants chosen in catalogues built especially for this purpose.[9,10] The observation of one individual target typically consists in recording 150 "scans" of the fringes using a modulation of the optical path in one arm of the interferometer. Under good weather conditions, the observation of one individual target takes about 15 minutes, so that up to 20 individual observations of scientific targets can be obtained during a night. Due to weather and technical down time, however, in about 100 available observing nights on the S1-S2 baseline for this survey, only about 540 observations of scientific targets were obtained.

The FLUOR Data Reduction Software (DRS)[11–13] was used to extract the raw squared modulus of the coherence factor between the two independent apertures. The extraction of the squared visibilities from the fringe packets recorded in the time domain is based on the integration of the squared fringe peak obtained by a Fourier transform of the fringe packet,[11] or equivalently by a wavelet analysis.[12] The interferometric transfer function of the instrument was estimated using the calibrator stars located before and after each observation of a scientific target. Calibrators chosen in this study are generally late G or K giants, whereas our target stars have spectral types between A0 and F2. Since the visibility estimator implemented in the FLUOR DRS depends on the actual spectrum of the target star, an appropriate correction must be applied to our data, otherwise our squared visibilities would be biased at a level of about 0.3%.[11] This correction can be based either on shape factors[11] or on a wide band model for estimating the calibrator's visibilities and interpreting the data.[14,15] The latter method was chosen for this work, and all the calculations presented here therefore take into account a full model of the FLUOR instrument, including the spectral bandwidth effects.

## 2.3 Preliminary results

For all scientific targets, we used a model consisting of a limb-darkened disk representing the photosphere surrounded by a uniform emission filling the whole field-of-view to simulate the effect of a possible circumstellar disk. The photospheric model is fixed using the estimated limb-darkened diameter from surface-brightness relationships and the linear limb-darkening coefficients of Claret.[16] Furthermore, we account for a possible oblateness of the photosphere, based on the measured $v \sin i$, as described in a previous paper.[4] The only free parameter of the fit is therefore the disc/star flux ratio. Fitting is performed using the Levenberg-Marquardt non-linear least squares curve fitting package `mpfit`[17] under the IDL interpreted language. The final error bar on the disk/star flux ratio includes two contributions: (i) the statistical error bar due to the scatter of the $V^2$ data points, and (ii) the systematic error bar due to the uncertainty on the stellar photospheric model. The results presented here are still preliminary, as we are still working on the final data reduction and analysis for a couple of stars in our sample.

The fitting procedure generally provides a reduced chi square ($\chi_r^2$) around 1 for most stars, implying that, one on hand, the observed stars can indeed be represented by the proposed model (oblate limb-darkened photosphere surrounded by a uniform circumstellar emission), and on the other hand, our error bars have been properly estimated. When the $\chi_r^2$ was found to be larger than 1, we conservatively assumed that the error bars on the measured $V^2$ had been underestimated by the DRS, and we renormalized the error bars before computing the final uncertainties on the fitted disk/star flux ratio. The final error bar on the disk/star contrast was typically around 0.3% based on typically 7 individual data points per star.

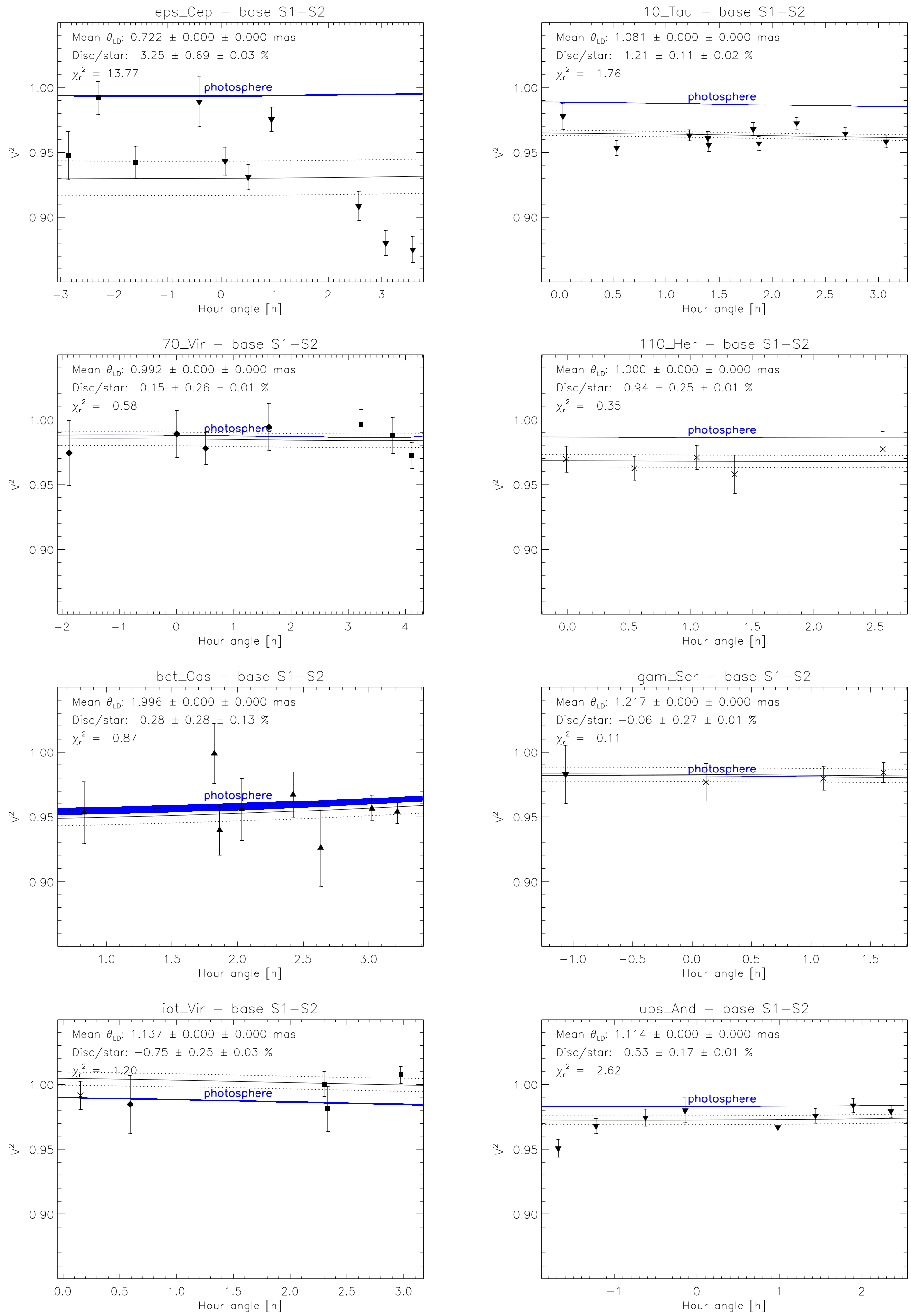


Figure 2. Illustration of our results on a few selected stars. The $V^2$ obtained on the short S1-S2 baseline are displayed as a function of hour angle. Stellar diameters have been fixed to their estimated value, hence the absence of error bars on this quantity in the insets. The width of the blue line represents the $3\sigma$ uncertainty on the stellar model. From top left to bottom right: $\epsilon$ Cep has a high $\chi_r^2$ due to its binary nature; 10 Tau is a clear excess detection with many data points. 70 Vir is a "typical" non-detection; 110 Her is a detection with a very small $\chi_r^2$; $\beta$ Cas features data of relatively poor quality and large error bars; $\gamma$ Ser is a non-detection with few data points and an exceptionally low $\chi_r^2$ (mostly due to the small number of data points); $\iota$ Vir is our most negative "anti-excess", with a $-3\sigma$ non-detection; $\upsilon$ And is a marginal detection (exactly at $3\sigma$), that we consider not to be significant in our statistical analysis.

Among our 43 survey targets, one star however showed a very large $\chi^2_r \simeq 13$ in the fitting procedure (see Figure 2). This star, $\epsilon$ Cep, was followed up with coronagraphic observations at the Palomar Hale 200-inch telescope, as we suspected the presence of a companion to be the reason for the large variations in the measured $V^2$. These coronagraphic observations confirmed the presence of a stellar companion around $\epsilon$ Cep, with a K-band flux ratio of $2.0\% \pm 0.5\%$. We note that this estimated flux ratio is mostly compatible with our estimation ($3.25\% \pm 0.69\%$), although it was obtained using an inappropriate model for this target (star + disk instead of binary star). This star is consequently removed from the forthcoming statistical analysis. We also removed from our analysis the eclipsing binary star $\alpha$ CrB, which was observed during an eclipse, but for which the presence of a close stellar companion is expected to prevent any warm dust from subsisting in an exozodiacal disk around the primary. We are therefore left with a final sample of 41 stars on which a statistical analysis can be performed. This sample comprises 22 stars with cold dust and 19 non-dusty stars. The repartition between spectral types is the following: 12 A-type, 14 F-type and 15 G- or K-type stars. A few representative examples of detections and non-detections are given in Figure 2.

### 2.4 First statistical trends

Among the 41 remaining stars in our statistical sample, 14 feature a formal detection of a circumstellar excess, i.e., the estimated disk/star flux ratio is at least three times larger than the estimated error bar. However, among these 14 formal detections, two are barely above $3\sigma$. Furthermore, these two stars ($\mu$ Her and $\upsilon$ And) have a rather large $\chi^2_r$ of about 2.6. We will therefore not consider these two detections as significant, all the more that the most significantly negative excess in our sample ($\iota$ Vir) is precisely at the $-3\sigma$ level. We are therefore left with 12 significant detections of K-band circumstellar excess around our 41 survey targets, which yields an overall occurence rate of $29\%^{+8\%}_{-6\%}$. In the following discussion, we will assume that the 12 detected excesses are associated with a population of hot dust grains, which we deem to be the most natural explanation. We note that faint companions might also explain some of our detections, although a significant fraction of our targets have been observed with single-aperture high-contrast imaging instruments or with multi-telescope infrared interferometers providing closure phase information, showing the absence of companion.

The repartition of the exozodi occurence rate as a function of spectral type and as a function of the presence of cold dust is illustrated in Figure 3. This figure shows an interesting trend, in that stars with cold dust tend to have a similar occurence rate of bright exozodis whatever their spectral type. Conversely, the occurence rate of bright exozodi around stars without a large reservoir of cold dust significantly depends on the spectral type. The behaviour of A-type stars seems different from that of solar-type stars (FGK) in that respect. It is particularly interesting to note that the presence of near-infrared excess emission seems to correlate with the presence of cold dust in the case of solar-type stars. These statistical trends are however still preliminary, and their low significance urges us to enlarge our sample before any definitive conclusion can be drawn on the occurence rate of the hot exozodi phenomenon.

## 3. EXTENDING THE SURVEY

Three main avenues can be considered for extending the survey:

- Within the current magnitude limit of FLUOR ($K < 4$), add new dusty targets recently discovered by the DUNES[18] and DEBRIS[19] surveys on the Herschel Space Observatory. These surveys are however not expected to increase very significantly our $K < 4$ sample.
- Increase the magnitude limit of FLUOR: this is the goal of the "JOUFLU" upgrade of FLUOR, which includes an upgrade of the detector. With this upgrade, we expect that the magnitude limit could be improved to $K \simeq 5$.
- Extend the survey to the Southern hemisphere. This is now possible thanks to the PIONIER instrument at VLTI, which provides a suitable limiting magnitude and accuracy ($H \simeq 5$ for high-precision visibilities).

In the following sections, we briefly introduce a new magnitude-limited ($K < 5$) all-sky sample that we have built to match the new capabilities of FLUOR and PIONIER, and that we plan to use to increase the statistical significance of our results.

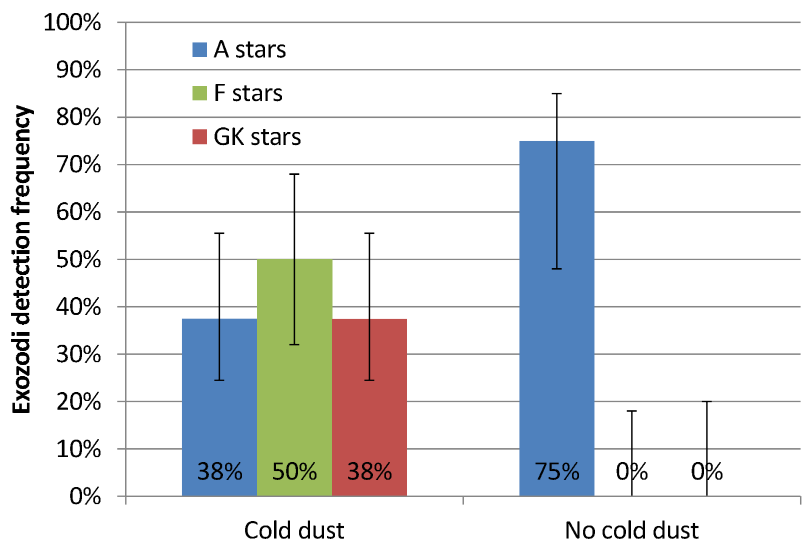


Figure 3. Preliminary statistical trend on the occurence of bright exozodiacal disks as a function of spectral type and as a function of the presence of massive cold dust reservoirs.

### 3.1 Goals and sample definition

One of the most interesting results of the FLUOR survey so far is the possible correlation between the presence of cold dust and hot dust for solar-type stars. Another interesting result is the difference in hot exozodi occurence rate between A-type stars and solar-type stars. In order to explore these correlations in a unbiased manner, we want to define a sample such that:

- the dusty and non-dusty sub-samples have the same number of stars, are spread similarly between the various spectral types, and have similar median magnitudes;
- the sample is evenly spread between spectral types A, F and G-K, if possible with similar mean magnitudes.

Based on these requirements, we have chosen to work along the following lines. First, we identify all the known debris disk host stars with $K < 5$ and spectral type A, F, G and K. From this sample, we remove all the stars that are known to be binaries with angular separations smaller than $5''$, as on the one hand they might affect the PIONIER observations, and on the other hand, the presence of close stellar companions may significantly affect the dynamics of the planetary system and thereby induce biases in our survey. We also remove all stars that look significantly bloated with respect to the expected main-sequence stellar diameter, based on surface-brightness estimations of their stellar angular diameters. This produces a sample of 107 dusty stars.

Similarly, we build a master sample of non-dusty stars, by using the Spitzer and Herschel catalogues of stars without any detected far-infrared excess. Using the same selection criteria, we end up with a "control" sample of 261 stars. From this sample, we will try to associate a "control" star to each dusty star, with the following requirements: (i) same spectral type, (ii) similar V- and K-band magnitudes, and (iii) close position in the sky, so that they can be observed successively on the same night, with similar observing conditions.

In order to appropriately match control stars with dusty stars, we define a "badness" criterion on the control stars, which includes the three items described above, and we perform an optimisation of the global badness on the whole sample. At the end of the selection process, most control stars are located within 20 degrees, 5 sub-spectral types (e.g., A0V with A5V) and one magnitude of their associated dusty star. This will ensure that we introduce no bias when comparing the dusty and non-dusty samples. We note however that the control sample is slightly brighter than the dusty sample (mean K-band magnitude of 4.0 instead of 4.3). Furthermore, nature has been kind enough with us that the number of stars in our magnitude-limited sample is well balanced between the three selected spectral categories (A, F and G-K), and that the mean K-band magnitude is similar for the three spectral categories (between 3.9 and 4.4 depending on spectral type).

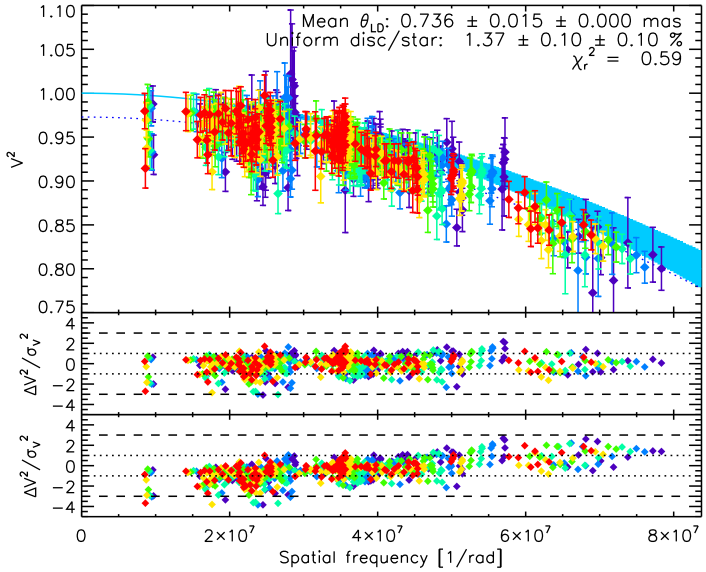


Figure 4. Squared visibilities obtained with VLTI/PIONIER on $\beta$ Pic, with baselines ranging from about 30 m to 130 m. Accuracies of $\sim$ 2% are commonly achieved on individual data points, which is suitable for our scientific goal. The various colours represent six of the seven spectral channels across the H band. The blue line represents the expected $V^2$ of the $\beta$ Pic photosphere, while the dotted line represents the best fit for a star-disk model. The two lower plots show the residuals of the fit when using a model of a limb-darkened photosphere surrounded by a uniform circumstellar emission (top) and when using only a limb-darkened photosphere (bottom). The residual plots clearly show that the sole photosphere cannot fit the whole data set properly, and that the addition of a circumstellar emission reconciles the model with the data set.

## 3.2 First results with VLTI/PIONIER

Before properly starting the exozodi survey with PIONIER, we performed some science demonstration observations in Fall 2011, in order to assess the capability of PIONIER to reach a sufficient accuracy on the squared visibilities. The highest spectral dispersion of PIONIER was used for these observations, with 7 spectral channels recorded across the H band. Among the results obtained during the Fall 2011 observing runs, we highlight here below the discovery of an H-band excess around the emblematic debris disk star $\beta$ Pic. The large data set obtained on this star is illustrated in Figure 4. It clearly shows the presence of resolved circumstellar emission, amounting to $1.37\% \pm 0.14\%$ when using a uniform emission model for the disk.

This kind of result is very similar to the detections obtained previously with CHARA/FLUOR,[2] VLTI/VINCI[6] or IOTA/IONIC.[7] However, in this case, we can also investigate the wavelength-dependence of the circumstellar excess, which was not possible before. When fitting a uniform circumstellar emission model to each spectral channel separately, we end up with the excess spectrum illustrated in Figure 5, almost parallel to the stellar spectrum. This result points towards stellar scattered light as the source of the circumstellar excess although hot dust (warmer than 1000 K) could also fit the data in a satisfactory way. The implications of this discovery on the $\beta$ Pic dust disk will be discussed in a forthcoming paper (Defrère et al., in prep.).

Based on these successful observations, we have started in April 2012 the magnitude-limited survey using the sample defined in Section 3.1. The first results confirm that PIONIER has a sufficient intrinsic accuracy on the $V^2$ to fulfil our scientific goals. We have also demonstrated that, with 6 (short) baselines and up to 7 spectral channels recorded simultaneously, PIONIER is much more efficient that the 2-telescope FLUOR interferometer for such a survey, as we observed up to 10 stars during a single night with PIONIER instead of (typically) 1 to 2 stars per night with FLUOR. Our first survey observations, which address targets and calibrators all across the sky in one single night, also allowed us to identify an unexpected behaviour of the $V^2$ on some baselines, showing a very high and clear correlation with the pointing direction.[20] We tentatively interpret this behaviour

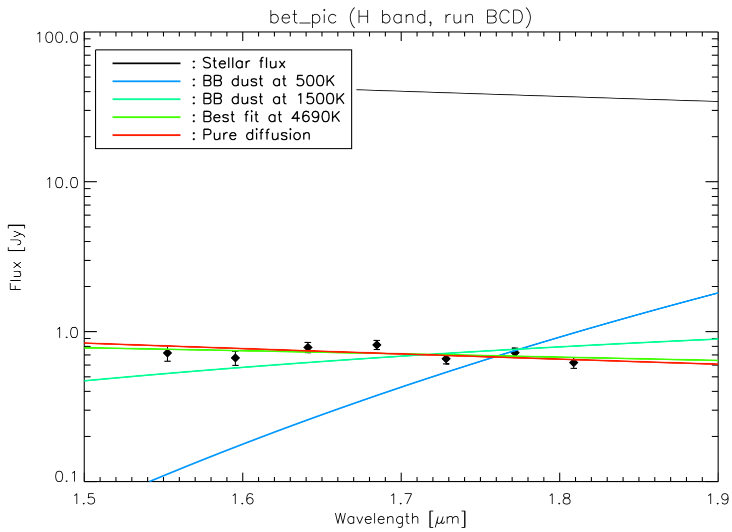


Figure 5. Circumstellar excess flux detected around $\beta$ Pic as a function of wavelength, assuming a uniform emission model. The stellar spectrum is shown as a black line for comparison. We have fitted the circumstellar excess with blackbodies of various temperatures, showing that a temperature higher than 1500 K is necessary to produce a good fit. Pure stellar light scattering (assuming grey grains) is also shown, suggesting that the circumstellar excess could originate from scattering rather than thermal emission.

to be due to polarization effects in the VLTI optical train, but further analysis is required before a definitive conclusion can be drawn.

## 4. CONCLUSIONS

Our survey for hot exozodiacal disks around nearby main sequence stars is now ongoing with VLTI/PIONIER, and will soon resume with CHARA/FLUOR when FLUOR comes back online after its upgrade and commissionning (probably in early 2013). With these two instruments, we plan to increase our statistical sample to about 200 stars (100 dusty and 100 non-dusty), which will provide us a large enough sample to draw statistically significant conclusions regarding the occurence of the hot exozodi phenomenon as a function of spectral type and its possible correlation with the presence of cold dust reservoirs. Furthermore, the low spectral resolution capability of PIONIER (and soon FLUOR) will significantly help us in the characterisation of the detected disks.

## 5. ACKNOWLEDGMENTS

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