Astronomy & Astrophysics manuscript no. h3878 February 21, 2003
(DOI: will be inserted by hand later)

The 1.2 mm image of the β Pictoris disk *

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Received date: Accepted date:

Abstract. We present millimeter imaging observations in the 1200 μm continuum of the disk around β Pic. With the $25''$ beam, the β Pic disk is unresolved perpendicularly to the disk plane ($\leq 10''$), but slightly resolved in the northeast-southwest direction ($26''$). Peak emission is observed at the stellar position. A secondary maximum is found 1000 AU along the disk plane in the southwest, which does not positionally coincide with a similar feature reported earlier at 850 μm. Arguments are presented which could be seen in support of the reality of these features. The observed submm/mm emission is consistent with thermal emission from dust grains, which are significantly larger than those generally found in the interstellar medium, including mm-size particles, and thus more reminiscent of the dust observed in protostellar disks. Modelling the observed scattered light in the visible and the emission in the submm/mm provides evidence for the particles dominating the scattering in the visible/NIR and those primarily responsible for the thermal emission at longer wavelengths belonging to different populations.

Key words. Stars: individual: β Pictoris – circumstellar matter – planetary systems: formation – protoplanetary disks ISM: dust, extinction

1. Introduction

Since its discovery by IRAS (e.g., Aumann 1984), the β Pictoris system has presented the prime example of a dusty disk around a main sequence star, partly because of its high degree of 'dustiness' ($L_{\rm IR}/L_\star = 2.5 \times 10^{-3}$, e.g. Lagrange et al. 2000) and partly because of its relatively close distance to the Earth (19.3 pc, Crifo et al. 1997), which makes it possible to obtain high quality data over the entire spectral range. Recent papers reviewing the physics of the disk around β Pic include those of Artymowicz 2000, Lagrange et al. 2000 and Zuckerman 2001. Considerable uncertainty existed regarding the age of the system, but most recent estimates place the stellar age close to only ten million years (12^{+8}_{-4} Myr, Zuckerman et al. 2001). This could open up the possibility that planet formation (nearing its final phases?) might actually become observable.

Since these reviews were written, new relevant information has been added to our knowledge of the β Pic system: Olofsson et al. 2001 reported the discovery of widespread atomic gas in the disk, a result recently confirmed and extended by Brandeker et al. 2002. These observations revealed the sense of disk rotation and that the northeast (NE) part of the gaseous disk is extending to the limit of the observations by Brandeker et al., viz. to at least $17''$ (330 AU) from the star. Several difficulties were encountered with these discoveries, such as the observed fact that the gas stays on (quasi-)Keplerian orbits, although radiation pressure forces in the resonance lines should accelerate the gas to high velocities and remove it on time scales comparable to the orbital period.

This needs to be addressed in the context of the origin and evolution of the gas and dust, i.e. whether one or both components are presently produced in situ in the disk or whether they (at least to some degree) constitute 'left-overs' from the star formation process, being of primordial origin. Takeuchi & Artymowicz 2001 have considered the interaction of gas and dust in a circumstellar disk, the dynamical evolution of which is critically depen-

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* Based on observations collected with the Swedish ESO Submillimeter Telescope, SEST, in La Silla, Chile.

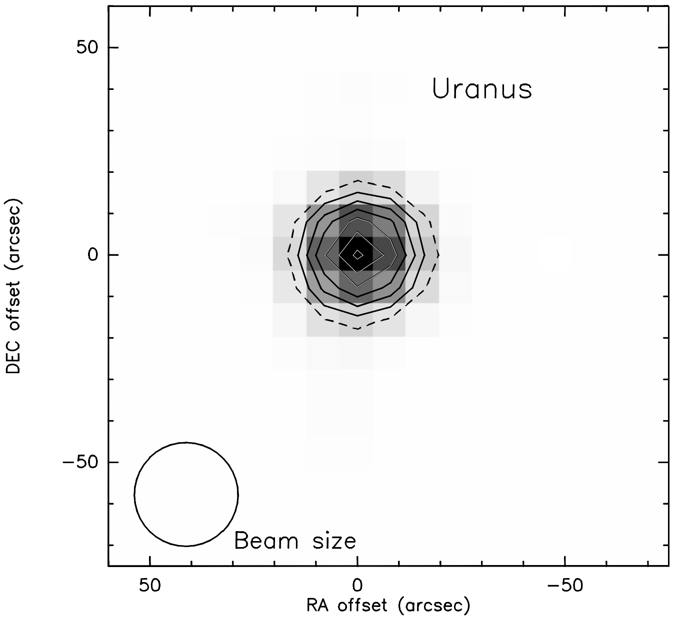

Fig. 1. The normalised SIMBA 1.2 mm image with 8″ pixels of the flux calibrator Uranus, the size of which was 3.″5 in diameter at the time of our observations and, hence, appeared point-like to SIMBA. Offsets in Right Ascension and Declination are in arcsec and the derived circular Gaussian beam of 25″ FWHM is shown in the lower left corner. During the scanning alt-az observations, the image rotates which would smear out any low-level features. Contour levels as in Fig. 2.

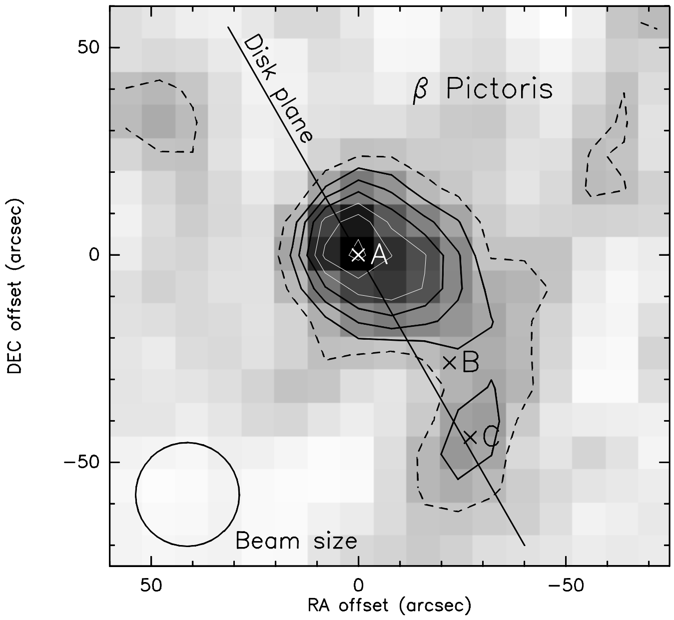

Fig. 2. The β Pic disk imaged at 1.2 mm with a pixel sampling of 8″. The lowest (dashed) contour corresponds to 2σ and increments are by $1\sigma = 3$ mJy/beam. The center coordinates $(0, 0)$ refer to the stellar position and offsets are in arcsec. Features discussed in the text are marked and the optical disk midplane is shown by the straight line at position angle 31.°5. The circular Gaussian beam of 25″ FWHM (~ 500 AU) is shown to scale in the lower left corner.

dent on the relative abundance of these species (see also Lecavelier des Etangs et al. 1998). Possible observational consequences, even relatively far from the central star, may become assessible with modern mm/submm cameras. With the aim to compare and to extend the results obtained at 850 μm with SCUBA by Holland et al. 1998, we performed imaging observations at longer wavelengths and, in this paper, we present the image of the β Pic disk at 1200 μm (1.2 mm).

The SIMBA observations and the reduction of the data are presented in Sect. 2. Our basic result, i.e. the 1.2 mm image of β Pic and its circumstellar disk, is found in Sect. 3, and in Sect. 4 the possible implications of these observations are discussed, where also other data are consulted. Finally, in Sect. 5, we briefly summarise our main conclusions from this work.

2. SIMBA observations and data reductions

The observations were performed with the SEST Imaging Bolometer Array (SIMBA) at the 15 m Swedish-ESO Submillimeter Telescope (SEST), La Silla, Chile, during the periods November 17 - 23 and 27 - 29, 2001. SIMBA has been developed by the Max-Planck-Institut für Radioastronomie, Bonn, in collaboration with the Astronomisches Institut der Ruhr-Universität Bochum. The 37 liquid helium cooled semiconductor elements are n-doped silicon chips, mounted on a saphire substrate. Projected on the sky, the 37 horn antennae have each an HPBW of 23″ and are spaced by 44″ in a hexagonal arrangement, covering about 4′. The spectral band pass is centered at 250 GHz (1200 μm) and has a full width at half maximum (FWHM) of 90 GHz.

As map centre, the equatorial coordinates of β Pic were used, viz. $05^{\rm h}47^{\rm m}17\overset{\rm s}{.}1$, $-51°03′59″$ (J 2000). Generally, the mapping was done in fast mode by scanning 600″ in azimuth and 400″ in elevation at the rate of 80″ per second and with a step size in elevation of 8″, oversampling the beam by about a factor of three. The zenith opacities were obtained by means of frequent sky dips and were on the average 0.22 at the beginning of our observing run, but improved to about 0.15 after a couple of days. The pointing of the telescope was regularly checked using the extragalactic radio source 0537 − 441 and/or the planet Saturn and was found to be within a third of the beamwidth.

Flux calibrations were based on observations of the planet Uranus. The brightness temperature of 94.8 K at 250 GHz implies a Uranus flux density of 38 Jy/beam, with an uncertainty of 5% (Griffin & Orton 1993). As is evident from Fig. 1, the spatial flux distribution of this point source (diameter 3.″5) is consistent with a circular Gaussian telescope beam, with the measured FWHM($\parallel$, $\perp$) = ($24\farcs9 \pm 0\farcs3$, $24\farcs6 \pm 0\farcs3$). The deviation from a circularly symmetric Gaussian beam pattern occurs at the 1% level of the peak value (−20 db).

In total, we recorded 171 maps with 21 hours of integration. These data were reduced by making use of the

MOPSI reduction software package[1] developed by Robert Zylka. This involved correcting for atmospheric extinction, cosmic rays and the variable sky background, as well as producing maps from the fast scanning mode. The sky noise was greatly reduced by correlating and removing the simultaneous flux level variations of the different bolometer channels.

3. Results

The $1200\,\mu$m image of the β Pic region is displayed in Fig. 2, where the displayed contours are chosen in compliance with Holland et al. 1998. The flux maximum, designated as feature A in the figure, is centered on the position of the star β Pic ($0''$, $0''$). At position angle 237° relative to A, an elongation of the emission in the NE-SW direction is discernable. For an assumed Gaussian source flux distribution, the deconvolved minor and major axes are $\leq 10''$ and $26''$, respectively, the latter corresponding to 500 AU. The disk emission extends to at least $55''$ (1050 AU) in the SW direction. In addition, faint emission protrudes south toward a 'blob' at ($-27''$, $-44''$). This feature C, at position angle 211.°5, is $52''$ (1000 AU) distant from the star and is thus not (whether real or not) positionally coincident with the $850\,\mu$m-SW blob of Holland et al. 1998 at ($-21''$, $-26''$) and identified as B in Fig. 2, but we note the following important facts: (1) this faint emission, extending straight south, is also apparent in the $850\,\mu$m image, (2) as is evident in Fig. 2, the position angle to blob C coincides with that of the midplane of the β Pic disk inferred from optical data (= 31.°5 + 180°; Kalas & Jewitt 1995, Heap et al. 2000), and (3) faint dust scattered light in this direction has been observed far from the star (1450 AU, Larwood & Kalas 2001). Toward the NE, the scattering disk has been claimed to extend even further from the star, to 1835 AU.

An about 2σ feature at ($+48''$, $+32''$) and pa = 57° (1100 AU) is discernable in our image, but which would again be significantly offset from a similar blob at ($+28''$, $+25''$) in the $850\,\mu$m data. In order to assess the reality of these faint features we have divided the raw data into different portions and then applied the same reduction procedures to these subsamples. The result of this exercise indicates that the ($+48''$, $+32''$) feature is an artefact introduced by the noise, as it is not seen in all frames, whereas blob C is persistently present in the final submaps.

The flux densities of both the β Pic disk (A) and the SW features (B and C) are presented in Table 1. The result for the peak flux obtained by Chini et al. 1991[2] with a single element bolometer at the SEST at $1300\,\mu$m, viz. 24.9 ± 2.6 mJy/beam, is in agreement with our array value of 24.3 ± 3.0 mJy/beam at 1200μm (cf. Fig. 3). The ratio of the peak flux A to that of blob C is 2.5 ± 0.8.

[1] http://www.ls.eso.org/lasilla/Telescopes/SEST/SEST.html

[2] We assume that these data refer to β Pic and not to α Pic as written in their Table 1.

Table 1. SIMBA 1200 μm flux densities of the β Pic disk

Feature	Relative Offset ($''$)	F_ν (1200 μm) (mJy/beam)	Remarks
A	(0, 0)	24.3 ± 3.0	**β Pic disk**
		35.9 ± 9.7	integrated over a radius of $40''$
B	(-21, -26)	...	**SW blob** (Holland et al. 1998): contaminated by β Pic disk
C	(-27, -44)	9.7 ± 3.0	**SW blob** (this paper)

4. Discussion

4.1. *The* β Pic *disk*

For widely adopted parameters, the stellar disk subtends an angle in the sky of less than 1 mas and the photosphere generates a flux density at the Earth of less than 1 mJy at $1200\,\mu$m. The stellar contribution to our SEST measurements can therefore be safely ignored. Also, any line emission in this band pass is likely to be totally negligible (Liseau & Artymowicz 1998, Liseau 1999 and references therein).

Assuming an opacity law of the form $\kappa_\nu = \kappa_0\,(\nu/\nu_0)^\beta$, the flux density at long wavelenghts from an optically thin source of a certain dust population can be expressed as

$$F_\nu = \frac{2k\kappa_0\Omega}{c^2\nu_0^\beta}\,\nu^{2+\beta}\int T_{\rm dust}(z)\,{\rm d}z \ . \tag{1}$$

If the particles dominating the emission at $850\,\mu$m and $1200\,\mu$m, respectively, can be assumed to yield the same integral, e.g. because they share the common temperature $T_{\rm dust}$ and/or occupy similar locations in space along the line of sight z, the average spectral index β can be obtained from our $1200\,\mu$m and the $850\,\mu$m fluxes by Holland et al. 1998, using

$$\beta = -2 + \frac{{\rm d}\log F_\nu}{{\rm d}\log\nu} = -2 + \frac{\log\left(F_{850}/F_{1200}\right)}{\log\left(1200/850\right)} \ , \tag{2}$$

yielding $\beta = 0.5$ for a point source at the stellar location. The index becomes $\beta = 1$, if we use the fluxes for the extended source, viz. integrated over a radius of $40''$ centered on the star. This includes blob B, contributing some 20% to the $850\,\mu$m flux. A 'correction' for this would again indicate a lower β value and we conclude that the dust in the β Pic disk has a shallow opacity index, perhaps even below unity (Dent et al. 2000 suggest $\beta = 0.8$). This is illustrated in Fig. 3, which displays the long wavelength spectral energy distribution of β Pic, together with weighted Rayleigh-Jeans spectra for $\beta = 0$, 1 and 2, and could mean that the grains dominating the millimeter-wave emission are different from those scattering most efficiently in the visual and the near infrared. This value of β is significantly lower than those found in the interstellar medium (ISM), where typically $\beta \sim 2$ (Hildebrand 1983), but it is similar to that found in *protostellar* disks (e.g., Beckwith et al. 1990, Mannings & Emerson 1994, Dutrey et al. 1996), indicating significant differences between the dust particles in the ISM and those in the β Pic disk. As was also already concluded by Chini et al. 1991, the presence of relatively large grains is suggested, with maximum radii in excess of 1 mm ($\max a/\lambda \gtrsim 1$). Intriguing, however, is the existence of such large grains possibly as far away as 1000 AU from the star (see, e.g., Takeuchi & Artymowicz 2001, Lecavelier des Etangs et al. 1998).

4.2. Weak dust features in the 1.2 mm image

The asymmetric flux distribution displayed in Fig. 2 may be surprising. In agreement with our observations, Chini et al. 1991 and Dent et al. 2000 too were unable to detect any emission in the northeast part of the disk, where we place a 3σ-upper limit on the mass of $0.2\,M_\oplus$ (see below; the dust temperature at 500 AU $T_{\rm dust} = 45$ K, when $T_{\rm dust}(r) = 110\,(r/26\,{\rm AU})^{-0.3}$ K, see Liseau & Artymowicz 1998).

Given the low signal-to-noise ratio (S/N), the reality of this lopsidedness is difficult to assess, but asymmetries in the β Pic disk have been noticed also at other wavelengths. For instance, in scattered light, the receding NE side of the disk extends much further and is much brighter than the SE disk. In contrast, the shorter, approaching SE disk seems much thicker (Kalas & Jewitt 1995, Larwood & Kalas 2001). The situation is reversed in the thermal infrared (albeit on smaller spatial scales), where the SW disk appears significantly brighter and more extended than the NE side (Lagage & Pantin 1994, Wahhaj et al. 2002, Weinberger et al. 2002). This could be due to a 'Janus-effect', i.e. the NE being dominated by 'bright' dust particles (high albedo, silicates), whereas in the SE, the majority of dust grains is 'dark' (high absorptivity, carbonaceous?). What would accomplish such uneven distribution in the disk is not clear, but large differences in albedo, by more than one order of magnitude, are not uncommon, for instance, in solar system material. Also, in order to understand the nature of feature C (and B) velocity information would be valuable.

Blob C would be situated in the disk midplane and on the *second* contour in the scattered light image of Larwood & Kalas 2001 ($22 < R < 25\,{\rm mag/arcsec^2}$, see also Kalas & Jewitt 1995). No obvious distinct feature is seen at its position. However, to be detectable with SIMBA at the SEST, any point source at mm-wavelengths would not be point-like at visual wavelengths, and its optical surface brightness could be very low.

To gain some quantitative insight we ran numerical models, exploiting Mie-theory, for a variety of plausible dust mixtures regarding the chemical composition and grain size distributions (for details, see Pantin et al. 1997). The equilibrium temperatures were found to be in the interval 16 K to 58 K and depending on the dust albedo and scattering phase function, the predicted integrated scattered light, to be consistent with our SEST observations, spans 8 magnitudes. The two most extreme cases considered were (1) bright cold dust (albedo = 1 at visual wavelengths, $T_{\rm dust} = 16$ K) which is scattering isotropically and has albedo = 0.2 at thermal wavelengths, which results in a spatially integrated R-magnitude of 17.3 and (2) dark warm dust (albedo = 0.02 in the visual, $T_{\rm dust} = 58$ K) which gives rise to 'comet scattering', i.e. 14% of isotropic at 90°, and has zero albedo at thermal wavelengths, resulting in an integrated R-magnitude of 25.6. These extreme cases are felt to be either too optimistic or too conservative and an intermediate case might be more appropriate. Our adopted model includes isotropically scattering dust at $T_{\rm dust} = 25$ K with albedo = 0.2 at visual and zero albedo at thermal wavelengths, yielding an integrated R-magnitude of 20. An about $10''$ source ($R = 25\,{\rm mag/arcsec^2}$) would thus be consistent with both the optical data and our SIMBA measurement and a deep R-band search might become successful. Similarly, the integrated 850 μm flux density is predicted to be slightly less than 18 mJy and should become readily detectable. However, blob C is situated outside the figure of Holland et al. 1998.

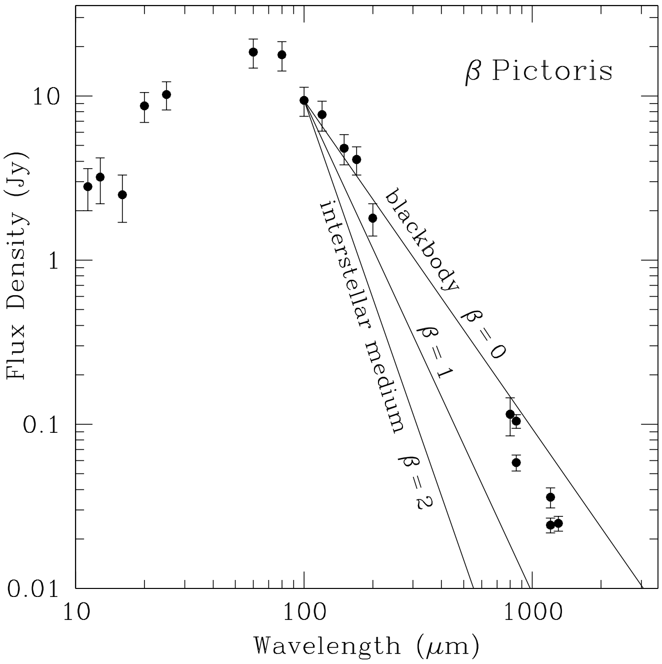

Fig. 3. The SED of the β Pic disk from 10 to 1300 μm. Data up to 200 μm are from Heinrichsen et al. 1999 ($52''$ to $180''$). The datum at 800 μm is from Zuckerman & Becklin 1993 (integrated over a radius = $25''$). The 850 μm data are from Holland et al. 1998 and refer to a $14''$ beam and to the integrated flux over a radius = $40''$. The latter should be comparable to our 1200 μm point for $40''$; the lower is for a $25''$ beam, and that at 1300 μm ($24''$ beam) is from Chini et al. 1991. For reference, the spectral slopes longward of 100 μm for three values of the dust emissivity index β, discussed in the text, are shown by the straight lines.

Feature C is perfectly aligned with the optical disk plane, and its (hypothetical) mass can be estimated from

$$M_{\rm dust} = \frac{D^2\,F_\nu}{\kappa_\nu\,B_\nu(T_{\rm dust})}\ \ , \tag{3}$$

where the distance D is assumed to be that of β Pic and the adopted *dust* absorption coefficient $\kappa_{250\,\rm GHz} \sim 1\,{\rm cm}^2\,{\rm g}^{-1}$. This estimate of κ_ν is probably correct within a factor of three (Beckwith et al. 2000 and references therein). For the dust temperature $T_{\rm dust} = 25$ K, the dust mass is of the order of ten lunar masses ($0.16\,{\rm M}_\oplus$), which would be comparable to the dust mass of the disk proper, being overall much warmer. Another factor of about three uncertainty stems thus from the dust temperature, provided $10\,{\rm K} < T_{\rm dust} < 60\,{\rm K}$.

The famous 'SW-blob' in the $850\,\mu$m image has received considerable interest by the debris disk community. According to Dent et al. 2000, this feature, labelled B in Fig. 2, is real. It is not readily apparent in our $1200\,\mu$m image, however, presumably due to the combination of low contrast and reduced angular resolution. To test this idea, we performed numerical experiments, i.e. convolving two point sources, at the appropriate positions of A and B and with varying flux ratios, with the SIMBA beam. Flux ratios, normalised to the peak value, which are consistent with our observations are in the range $0.25 - 0.45$, with the most compelling being about 0.3 (comparable to that for blob C). In combination with feature C, blob B accounts for the southward bridge seen in Fig. 2.

For radiation mechanisms generating power law spectra and/or thermal dust emission from blob B, the spectral slope is given by $\alpha = \beta_A + 2 - \Delta \log R_\lambda / \Delta \log \lambda$, where β_A, as before, refers to $A = (0'', 0'')$, i.e. the β Pic disk, and where $R_\lambda = [F_\nu(A)/F_\nu(B)]_\lambda$ and $\lambda = 850\,\mu$m or $1300\,\mu$m. Because of the relatively low S/N of the SCUBA and SIMBA data, the actual flux ratios are highly uncertain and, furthermore, calibration uncertainties and telescope beam effects could potentially introduce large errors. The combined observations of blob B suggest $\log{(R_{850}/R_{1200})} \sim 0$, yielding $\beta_B \sim \beta_A$, i.e. consistent with the spectrum of A.

5. Conclusions

Based on $1200\,\mu$m imaging observations of the circumstellar dust of β Pic we conclude the following:

- At $25''$ resolution, the $1200\,\mu$m image of the β Pic disk is slightly resolved in the NE-SW direction, but remains unresolved perpendicularly (NW-SE). In addition, the emission appears asymmetric and extends further SW-S to more than 1000 AU away from the star. Maximum emission (= 24 mJy) is observed toward the position of the star.
- Combining our $1200\,\mu$m map with that by Holland et al. 1998 at $850\,\mu$m we infer that the dust size distribution in the β Pic disk is significantly different from that in the general interstellar medium and appears more reminiscent of that found in protostellar disks. We argue that the thermal emission is dominated by dark big particles and that these grains constitute a population different from that dominating the scattering in the visible/NIR part of the spectrum.
- From the examination and numerical simulations of the available data (optical and submm/mm) for the southwestern blobs/extensions seen in the SIMBA maps we conclude that their reality can at present neither be excluded nor can, on the basis of the available evidence, their existence be fully confirmed.

Acknowledgements. We are grateful to Dr. José Afonso, who made available to us the Uranus calibration data, and to the SEST staff for providing additional observations. The critical comments by the anonymous referee are highly appreciated.

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