

# Image of a close and planetary-mass companion to $\beta$ Pictoris<sup>★</sup>

A.-M. Lagrange<sup>1</sup>, D. Gratadour<sup>2</sup>, T. Fusco<sup>3</sup>, D. Ehrenreich<sup>1</sup>, G. Chauvin<sup>1</sup>,  
D. Mouillet<sup>1</sup>, G. Rousset<sup>3</sup>, D. Rouan<sup>2</sup>, F. Allard<sup>4</sup>, and NAOS Consortium<sup>1,2,3</sup>

<sup>1</sup> Laboratoire d'Astrophysique de l'Observatoire de Grenoble, Université Joseph Fourier, CNRS, BP 53, 38041 Grenoble, France  
e-mail: anne-marie.lagrange@obs.ujf-grenoble.fr

<sup>2</sup> LESIA, Observatoire de Paris, 5 place Jules Janssen, 92195 Meudon, France

<sup>3</sup> Office National d'Études et de Recherches Aérospatiales, 29 avenue de la Division Leclerc, 92322 Châtillon, France

<sup>4</sup> Centre de Recherche Astronomique de Lyon, 46 allée d'Italie, 69364 Lyon cedex 7, France

Received date / Accepted date

## ABSTRACT

**Context.** Since the discovery of its dusty disk in 1984,  $\beta$  Pictoris has become the prototype of young early type planetary systems, and there are now various indications that a massive Jovian planet is orbiting the star at  $\sim 10$  AU. However, no planets have been detected around this star so far.

**Aims.** Our goal is to investigate the close environment of  $\beta$  Pic, searching for planetary companion(s).

**Methods.** Deep adaptive-optics  $L'$ -band images of  $\beta$  Pic were recorded using the NaCo instrument at the Very Large Telescope.

**Results.** A faint point-like signal is detected at a projected distance of  $\approx 8$  AU from the star, within the North-East side of the dust disk. Various tests were made to rule out with a good confidence level possible instrumental or atmospheric effects as an origin for this signal. Moreover, there are strong evidences that the detected candidate companion is in fact a close, bound companion to  $\beta$  Pic. Its apparent  $L'$  magnitude of 11.2 would indicate a typical temperature of  $\sim 1500$  K and a mass of  $6\text{--}8 M_{\text{Jup}}$ . If confirmed, it could explain the main morphological and dynamical peculiarities of the  $\beta$  Pic system. It would be the first planet imaged around an early-type star, but also the first planet ever imaged so close to its parent star, possibly formed through core accretion.

**Key words.** Instrumentation: adaptive optics – stars: early-type – stars: planetary systems – stars: individual ( $\beta$  Pic)

## 1. Introduction

Understanding planetary systems formation and evolution has become one of the biggest challenges of astronomy, since the imaging of a debris disk around  $\beta$  Pictoris in the 80's (Smith & Terrile 1984) and the discovery of the first exoplanet around the solar-like star 51 Pegasi during the 90's (Mayor & Queloz 1995). While  $\sim 15$  debris disks – disks containing dust which is not primordial but produced by collisions among larger rocky bodies – have been resolved at optical wavelengths today,  $\beta$  Pic, a A5V star at a distance of 19.3 pc (Crifo et al. 1997), remains the best studied young ( $\sim 12$  Myr; Zuckerman et al. 2001) system, with an impressive amount of indirect signs pointing towards the presence of planets.

The disk shows a relative inner void of matter inside 50 astronomical units (AU). Several asymmetries have been identified in the disk at optical (Kalas & Jewitt 1995, Heap et al. 2000) and infrared (Telesco et al. 2005) wavelengths, as well as a warp at  $\sim 50$  AU (Mouillet et al. 1997; Heap et al. 2000). The warp is well reproduced by the deformation induced on colliding planetesimals by a giant planet or brown dwarf on a slightly in-

clined orbit within 50-70 AU from the star (Mouillet et al. 1997, Augereau et al. 2001). Silicate dust is observed as circumstellar rings at 6, 16, and 30 AU from the star (Okamoto et al. 2004), which could be explained by the presence of a 2–5-Jovian-mass ( $M_{\text{Jup}}$ ) planet at  $\sim 10$  AU from the star (Freistetter et al. 2007). Evaporating star grazing comets have been evidenced (see, e.g., Lagrange et al. 2000 for a review) and dynamical simulations showed that the gravitational perturbation of at least one giant planet at  $\sim 10$  AU can account for the observed rate of evaporating bodies (Beust & Morbidelli 2000). However, no planets have been detected so far, either through direct imaging or through radial velocity studies, due to the instrumental limitations of both techniques (Galland et al. 2006). In particular, the high spatial resolution imaging detection capabilities were so far limited to distances typically  $\geq 15\text{--}20$  AU.

We used the NAOS-CONICA instrument (NaCo), installed on the Very Large Telescope UT4 (Yepun) set in Paranal (Chile), to benefit from both the high image quality provided by the Nasmyth Adaptive Optics System (NAOS; Rousset et al. 2003) at infrared wavelengths and the good dynamics offered by the Near-Infrared Imager and Spectrograph (CONICA; Lenzen et al. 2003) detector, in order to study the immediate circumstellar environment of  $\beta$  Pic.

Send offprint requests to: A.-M. Lagrange

<sup>★</sup> Based on observations collected at the European Southern Observatory, Chile, ESO; runs 072.C-0624(B) and 60.A-9026(A); and observations made with the Space Telescope Imaging Spectrograph on board the NASA/ESA Hubble Space Telescope.

## 2. Observations and data reduction procedures

### 2.1. Observations

$L'$ -band images of  $\beta$  Pic ( $V = 3.8$ ,  $L' = 3.5$ ) were obtained between 2003 November 10 and 2003 November 17 with NaCo. The visible wavefront sensor was used with the  $14 \times 14$  lenslet array, together with the visible dichroic. We used the CONICA L27 camera, which provides a pixel scale of  $\sim 27$  mas. Saturated images of  $\beta$  Pic were recorded, with detector integration times (DITs) of 0.175 s and number of detector integrations (NDIT) of 100 or 200. Every two exposures<sup>1</sup>, spatial offsets were applied in order to allow sky and instrumental background removal.

Non-saturated images were also recorded to get images of the stellar point spread function (PSF) as well as a photometric calibration. In such case, we added the Long Neutral Density filter (transmission  $\sim 0.018$ ) in the CONICA optical path, and recorded images with DITs of 0.4 s. In addition, the binary IDS 22141S3712 (separation  $\rho = 6\,630 \pm 10$  mas, position angle  $PA = 302.06 \pm 0.07^\circ$ ; van Dessel & Sinachopoulos 1993) was observed on November 11 as astrometric calibration. A mean plate scale of  $27.105 \pm 0.041$  mas and a true North orientation of  $-0.10 \pm 0.07^\circ$  were derived and used to calibrate all  $\beta$  Pic images.

Saturated and non saturated exposures were taken on the reference star HR 2435 (AOII,  $V = 4.4$ ). Reference stars are used to correct for the star halo (the wings of the PSF) present in the saturated exposures. To optimize the removal of any fixed speckle,  $\beta$  Pic and HR 2435 were observed, as much as possible, at close parallactic angles. Finally, twilight flat fields were also recorded in  $L'$  band.

The observing conditions varied from exceptional (coherent energy  $EC > 70\%$ <sup>2</sup>, coherent time  $\tau_0 > 20$  ms) to reasonable ( $EC \sim 50\%$ ,  $\tau_0$  of a few ms), and sometimes not so good ( $EC \sim 20\text{--}35\%$ ,  $\tau_0 \sim 1\text{--}2$  ms), over the run; the data quality varies accordingly. The best data set on  $\beta$  Pic was obtained on November 10. In the following, we will describe three sets of data: (A) the very best set obtained on November 10; (B) a set of data with slightly poorer image quality obtained on the same night, with a shorter total exposure time, and (C) a set of data with poorer image quality obtained on November 13. However, Set C is representative of the best data obtained in the nights following November 10. The instrumental configurations and the status of image quality for these three data sets can be found in Table 1.

### 2.2. Data processing

The first step was to obtain stack images of  $\beta$  Pic and the reference star. To do so, we used two different approaches:

- All  $\beta$  Pic and HR 2435 data were first processed using the standard routines from the `eclipse` library for bad pixel removal, flat fielding, sky subtraction, and jittering of individual images. Special care was taken to correct for the instrumental background. The best results were obtained when estimating for each image the sky by averaging the 2 previous and 2 following offset images.
- The three data sets were also treated using improved softwares dedicated to adaptive optics (AO) image processing.

<sup>1</sup> An exposure is completed after  $DIT \times NDIT$ .

<sup>2</sup> Since it is not possible to measure the Strehl ratio on our saturated data, we can only use the information provided by NAOS to assess the image quality. The coherent energies are those measured by the system in  $K$  band.

After a classical flat field correction, sky background was subtracted from each image by selecting another image of the jittered sequence, close enough in time to ensure good sky subtraction, but far enough in the plane of the camera to minimize the effect of the scattered light from the star. The sequence of images has then to be recentered very accurately to preserve the spatial resolution when averaging the frames. To estimate the offsets parameters between the images, a maximum likelihood algorithm was used to recenter the images at the level of the tenth of a pixel or better, even with very noisy images, as in the case of thermal infrared imaging (for a full description of this method, see Gratadour et al. 2005). The same overall process was used for both the object and the reference.

The second step was to remove the PSF wings from the saturated images of  $\beta$  Pic and search for possible companions. To do so, we first divided  $\beta$  Pic images by the ones of HR 2435 obtained under similar conditions (same DIT, NDIT, and pupil position). We then computed the scaling factor to be applied to the reference in order to scale its flux to that of  $\beta$  Pic. We then subtracted the reference images to the  $\beta$  Pic ones. Both processes imply to recenter both data sets with a precision of less than a pixel (typically 1/4 pixel). For data sets processed with `eclipse`, the offset between the star and the reference was estimated using the divided and subtracted images. For the data sets processed with the improved recentering software, the two final images (reference and object) were recentered with respect to each other using the method described in the previous paragraph.

The saturated images of the three data sets were also processed with deconvolution technics to find out possible companions. We have used the MISTRAL algorithm (Mugnier et al. 2004) developed at ONERA. This algorithm is based on a maximum a posteriori scheme and allows to estimate the most likely offset between a given image and a reference. A linear-quadratic regularisation is added to optimally control the noise amplification in the deconvolution process without penalizing the sharp-edge objects. MISTRAL has been successfully applied during the last ten years on various data coming from all large telescopes and their AO systems all around the world. In our particular case, one of the main interest of MISTRAL is that the result is obtained by an iterative minimization of an explicit criterion representing the difference between the actual image and the object to be estimated. It has been shown (Mugnier et al. 2004) that the criterion is convex and thus has a unique minimum whatever the starting point. Practically, this means that the result does not rely on the relative centering of the image and the reference. Nevertheless, MISTRAL relies on a strict convolution process between image and reference which is not the case for our saturated data. A first step is therefore to perform a posteriori correction of saturated part of the image and reference. This is done using a simulated Airy pattern. The top of the Airy pattern replaces the image saturated pixels. The pixel level is adjusted using the first Airy rings. Such a correction is possible because of the very good Strehl ratio on the image. Meanwhile, if this a posteriori correction does not significantly affect the restitution of the object structures, it could obviously degrade the relative photometry. Hence, the deconvolution process is an alternative approach (compared to reference subtraction and division) for the image processing which is less sensitive to image versus reference centering. It allows us to provide the best measurements of PA and  $\rho$  between any detected candidate companion (CC) and  $\beta$  Pic (to 1/10 of a pixel); it can-

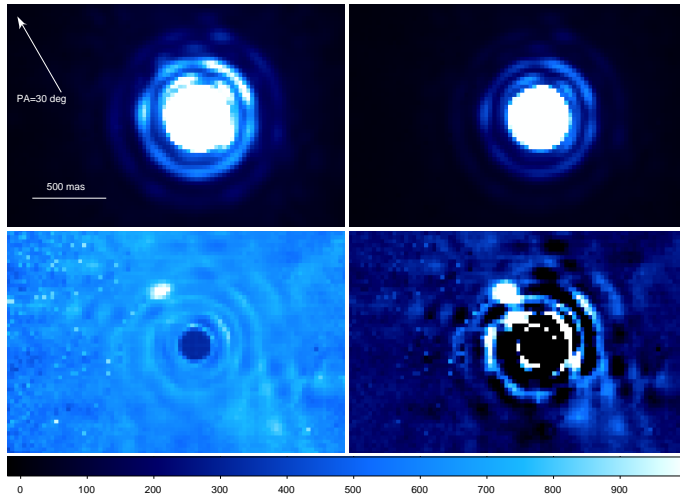
**Table 1.** The three data sets used in this study.

Set	Star	Date	DIT (s)	NDIT (s)	$t_{\text{exp}}(s)$	$\pi^a$	sec $z$	$\langle EC \rangle^b$	$\langle \tau_0 \rangle^c$ (ms)
A	$\beta$ Pic	2003-11-10	0.175	200	665	-18/-9	1.125/1.119	62.71	11.47
	HR 2435	2003-11-10	0.175	200	630	-20/-12	1.148/1.140	63.06	10.65
B	$\beta$ Pic	2003-11-10	0.175	100	420	-27/-19	1.138/1.127	57.94	8.08
	HR 2435	2003-11-10	0.175	100	420	-28/-20	1.161/1.149	60.23	9.70
C	$\beta$ Pic	2003-11-13	0.175	200	385	-24/-19	1.161/1.149	46.94	4.50
	HR 2435	2003-11-13	0.175	200	350	-22/-17	1.150/1.144	44.99	2.72

<sup>a</sup> Range of parallactic angles at the start/end of the observation.

<sup>b</sup> The average coherent energy as estimated on-line by AO.

<sup>c</sup> The average coherence time as estimated on-line by AO.



**Fig. 1.**  $\beta$  Pic and HR 2435 recentered and saturated  $L'$  images (top left and top right, respectively) in data set A. Below are the divided (bottom left) and subtracted (bottom right) images. North is up and East is to the left. A candidate companion is clearly detected at a PA of  $\approx 33^\circ$ , i.e., along the NE side of the disk, at a separation of about  $0''.44$  from the star.

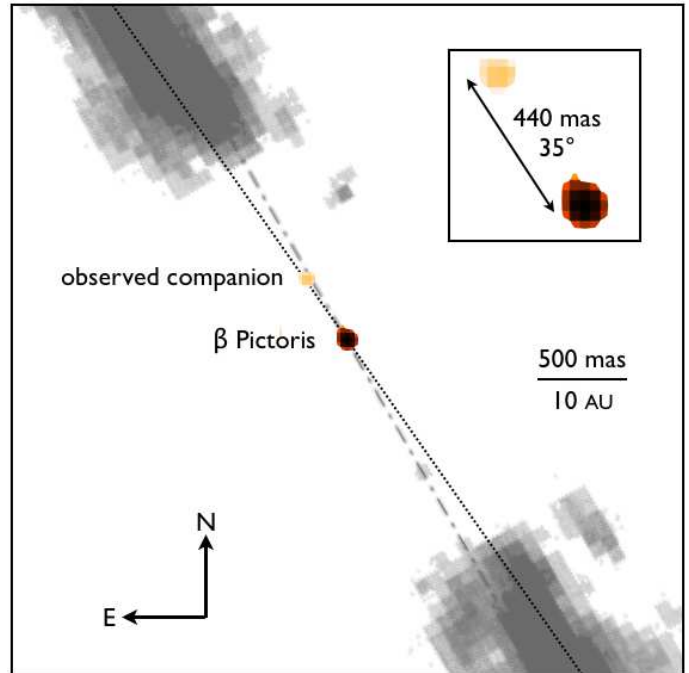
not however bring reliable photometric constraints due to the use of saturated images.

### 3. A candidate companion in the $\beta$ Pic disk?

#### 3.1. Results from the highest-quality data (set A)

With the different methods described previously, a CC is seen at the same location. Figure 1 gives the results obtained for the best data set (A) using the Gratadour et al recentering method. A point-like signal (hereafter, the CC) is clearly visible in the divided and subtracted images, at a PA of  $\approx 33^\circ$ , i.e., along the NE side of the disk, at a separation of about  $0''.44$  from the star. The maximum of the signal is about 190 ADU. Figure 2 gives the result of the deconvolution analysis. Using this method, we derive a separation of  $444 \pm 3$  mas and a PA of  $35.12 \pm 0.44^\circ$  relative to the primary.

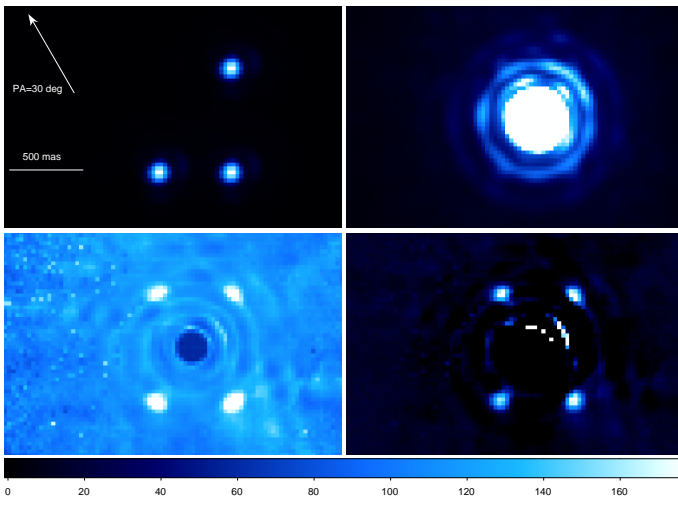
The fact that we detect the same signal with different methods clearly shows that it is not due to the reduction process. In particular, the result of the deconvolution rules out any effect that could be introduced by imperfect estimation of the offset between  $\beta$  Pic and HR 2435 saturated images due, for instance, to a possible contribution of the disk. We did check anyway that the disk signal is very faint and not significantly asymmetric.



**Fig. 2.** Our deconvolved NaCo  $L'$ -band image of  $\beta$  Pic and the observed CC (the inlet shows a zoom) scaled to the 1996 ADONIS  $J$ -band image of the disk that revealed its inner warp (Mouillet et al. 1997). The mid-plane of the outer disk is represented by the dash-dotted line (with a PA of  $\sim 30^\circ$ ); the midplane of the inner disk is warped by  $5^\circ$  with respect to the outer disk and indicated by the dotted line.

To rule out detector effects, we looked for possible remanence that could occur because our images are saturated. Indeed, for a given image, a very faint remanence signal (a few ADU) is present at the location of the previous offset position, but disappears in the next image. As 10 images are recorded before the star returns to a given offset position, we conclude that remanence effects can not explain the observed signal.

Artefacts due to the very good but still imperfect AO correction are still possible. However, aberrations due to a modulation of the deformable mirror would generally lead to the presence of either symmetrical or anti-symmetrical patterns. Static aberrations should be present equivalently around  $\beta$  Pic and HR 2435, as both stars were observed with similar pupil configurations. To further test the possible impact of an imperfect removal of static speckles due to the variation of the parallactic angle during the observations of  $\beta$  Pic and HR 2435 (up to  $8^\circ$ ), we processed individual pairs of data of  $\beta$  Pic and HR 2435 taken with parallactic angles equal within  $\pm 0.4^\circ$  and added up the individual subtracted



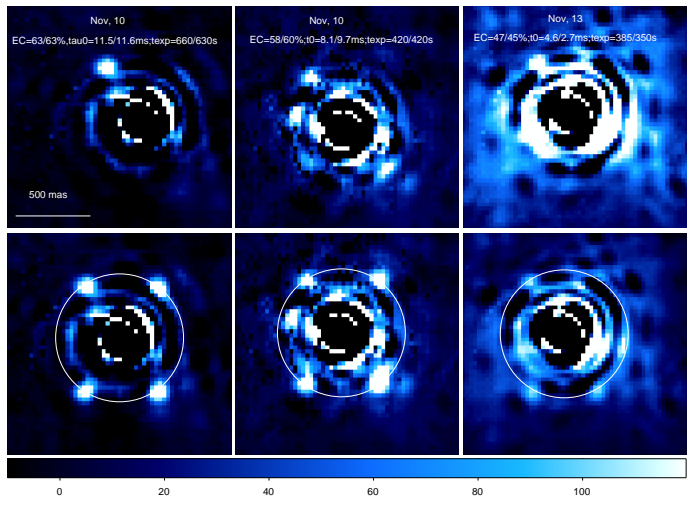
**Fig. 3.** Top left: simulated planets at PA of  $150^\circ$ ,  $210^\circ$  and  $330^\circ$ . Top right: composite image of  $\beta$  Pic plus the fake planets. Bottom left: division of the composite image by the saturated image of HR 2435. Bottom right: scaled subtraction of the composite image by the saturated image of HR 2435. Note that even a slight (0.3 pixel) relative offset between  $\beta$  Pic and HR 2435 impacts the resulting shape of the fake planets as much as the candidate one. In particular, triangular shapes can be observed, due to the proximity of the slightly inner Airy ring.

images. The CC is still present and appears slightly sharper (but still compatible with the instrumental resolution). In addition, since the same signal is also observed a few nights apart (see below), we conclude that quasi-static aberrations are unlikely.

To further assess the reality of the detection and constrain the CC photometry, we added three ‘fake planets’ at similar separations but different PA ( $150^\circ$ ,  $210^\circ$ , and  $350^\circ$ ) to the recentered and stacked image of  $\beta$  Pic. The fake planet images were generated by scaling and shifting an unsaturated image of  $\beta$  Pic taken during the same night so that the observed fluxes after scaling are similar to that of the observed CC. We then subtracted the scaled image of HR 2435 to that of the composite image. The result is shown in Figure 3, from which it is clear that the fake planets produce features similar to the observed signal. To match the level of the observed signal, the magnitudes of the fake planets must be  $\sim 11.2$ . This corresponds to a contrast of about 7.7 between  $\beta$  Pic and its CC. We conservatively estimate a precision of  $+10\%$  on the fluxes and hence a magnitude of  $L' = 11.2^{+0.1}_{-0.2}$  for the CC.

### 3.2. Results from lower quality data (sets B and C)

We processed all the other sets of data using the eclipse software. It quickly appeared that the detection becomes more marginal when the exposure time and/or the image quality decrease. For the best remaining sets in terms of atmospheric conditions and relative parallactic angle between  $\beta$  Pic and HR 2435 (described in Section 2.1 and Table 1), we used our more efficient reduction procedure. The results are shown in Figure 4. The same point-like signal is seen in both cases, with however a lower signal-to-noise ratio. This is due to the lower exposure times and the (slightly) poorer image qualities. This is illustrated in Figure 4, where we also added fake planets to the data sets B and C. The fake planet signals are, as the CC signal, much less detectable under these conditions; hence the results from our 3 data sets are consistent.



**Fig. 4.** Top: reduced images for sets A, B and C. Bottom: composite images for the same sets (see text).

## 4. Bound companion or background object?

With these data alone, it is not excluded that the CC could be a foreground or background object. To definitely test this hypothesis, second epoch measurements are needed. Using the known  $\beta$  Pic proper motions, we estimated the position of the CC if it was a background object down to 20 years before and up to 5 years after 2003 November. It appears that if the CC is a background object, it would be closer than  $0''.2$  to  $\beta$  Pic in 2008 and hence, not detectable with current technics.

To our knowledge, the highest angular resolution and dynamical data available are the coronagraphic data taken in 1997 September with the Space Telescope Imaging Spectrograph (STIS; Woodgate et al. 1998) on board the *Hubble Space Telescope* (Heap et al. 2000). These authors were able to probe the close stellar environment down to  $0''.75$  from  $\beta$  Pic. They did not report any CC in their images at the expected location of  $0''.9$  North and  $0''.25$  East to  $\beta$  Pic. Based on STIS detection limits, all objects brighter  $V \leq 17$  would have been detected. Red giants or supergiants, for their distances would bring them unrealistically far from us. If we consider a foreground or background stellar field contaminant, it would therefore have a large ( $V - L \geq 5.8$ ) color, i.e a spectral type later than mid-M. Based on a number density of L dwarfs of  $1.9 \times 10^{-3} \text{ pc}^{-3}$  given by Burgasser (2001) and Cruz et al. (2003), the probability of finding a foreground or background field L dwarf in a region of 500 mas radius around  $\beta$  Pic and with  $L' = 11.2$  is about  $10^{-10}$ . Without any assumption on the contaminant spectral type, one can use galactic population model outputs to estimate the probability to find any ( $L' \leq 12$ ) galactic object at 500 mas from  $\beta$  Pic. We find a low probability of  $6 \times 10^{-5}$ . Last, we cannot strictly rule out a contamination by an extragalactic source, such as a high-redshift quasar. In conclusion, a contamination appears very unlikely. In addition, the fact that the candidate companion falls into the disk strongly favors that it is bound to the star.

## 5. Implications on the understanding of the $\beta$ Pic system

With an  $L'$  magnitude of  $11.2^{+0.1}_{-0.2}$ , and assuming a distance of  $19.3 \pm 0.2$  pc and an age of  $12^{+8}_{-4}$  Myr (Zuckerman et al. 2001), the mass of the CC is estimated to  $9^{+4}_{-2} M_{\text{Jup}}$  using COND mod-

els (Baraffe et al. 2003) and  $8_{-2}^{+4} M_{\text{Jup}}$  using DUSTY models (Chabrier et al. 2000). The planet should still be in the phase of cooling: Dusty and COND models predict effective temperatures of 1 400 and 1 600 K, respectively.

The validity of these models in the case of young planets formed by core accretion has been recently questioned (Marley et al. 2008) on the basis that the accretion shock might impact the planet initial internal entropy and its subsequent early thermal evolution. These authors claim that young giant planets could be significantly cooler and fainter than predicted so far. However, the treatment of the accretion shock is still a matter of debate. The impact of the initial disk mass is also to be studied. This may be important in the present case as  $\beta$  Pic is significantly more massive than the Sun. We can already note that a companion at a true separation of  $\sim 8$  AU could not be significantly more massive than  $10\text{--}20 M_{\text{Jup}}$  since otherwise it would have been detected through radial velocity measurements, as shown by a detailed analysis that will be presented in a forthcoming paper (Desort et al., in preparation).

If the observed projected separation happens to be the physical one or close to the physical one, then the companion explains three very intriguing and so far unique characteristics of the  $\beta$  Pic system: the warp in the inner disk, the inner belts and the falling evaporating bodies (Freistetter et al. 2007). Mouillet et al. (1997) and Heap et al. (2000) showed that the warp of the disk constrains the (mass  $M_p$ , semi-major axis  $a$ ) domain of the planet as follows:

$$\log(M_p/M_\star) + 2 \log a + \log t \approx 6.7, \quad (1)$$

where  $M_\star = 1.8 M_\odot$  (Crifo et al. 1997) and  $t$  is the age of the star. Given an age  $t = 12$  Myr, masses  $M_p = 6$  and  $13 M_{\text{Jup}}$  give  $a = 9.7$  and  $7.6$  AU, respectively, nicely bracketting the measured projected separation. This further strengthens the likelihood that the observed CC is the planet causing the warp.

This companion could be the first extrasolar planet ever imaged so close to its parent star: 8 AU. In particular, it would be located well inside the orbits of the outer planets of the Solar System. Contrary to the other planetary-mass companions imaged at separations  $\gtrsim 40$  AU, such as 2M1207 b (Chauvin et al. 2004), AB Pic b (Chauvin et al. 2005), CHXR 73 B (Luhman et al. 2006), HD 230030 (Metchev & Hillenbrand 2006), or 1RXS J160929.1-210524 (Lafrenière et al. 2008),  $\beta$  Pictoris b might well have formed through core accretion. In such a case, ie if the companion is bound to the star and produced by core accretion, then its magnitude does not fit Marley et al. (2008) present predictions.

Further direct imaging observations should allow to constrain the planet orbit and hence measure the planet dynamical mass. This would in turn allow to test the models of planet formation. This is dramatically needed as the evolutionary models are not calibrated with real data in these ranges of masses and ages. Finally, we note that unfortunately, if the projected separation is the physical one, the planet orbital period is about 16 years and should be at present time much closer to the star and hence undetectable with NaCo.

*Acknowledgements.* We acknowledge financial support from the French Programme National de Planétologie (PNP, INSU), as well as from the French Agence Nationale pour la Recherche (ANR). These results have made use of the SIMBAD database, operated at CDS, Strasbourg, France. We also thank the ESO staff for its help during the NaCo observations. We thank J.-C. Augereau for useful inputs. AML thanks also P. Rubini for his help on the lay out of the paper.

## References

- Augereau, J.-C., Nelson, R. P., Lagrange, A.-M., Papaloizou, J. C. B., & Mouillet, D. 2001, A&A, 370, 447
- Baraffe, I., Chabrier, G., Barman, T. S., Allard, F., & Hauschildt, P. H. 2003, A&A, 402, 701
- Beust, H., & Morbidelli, A. 2000, Icarus 143, 170
- Burgasser, A. 2001, PhD Thesis, California Institute of Technology
- Chabrier, G., Baraffe, I., Allard, F., & Hauschildt, P. H. 2000, ApJ, 542, 464
- Chauvin, G., Lagrange, A.-M., Dumas, C., et al. 2004, A&A, 425, L29
- Chauvin, G., Lagrange, A.-M., Zuckerman, B., et al. 2005, A&A, 438, L29
- Crifo, F., Vidal-Madjar, A., Lallement, R., Ferlet, R., & Gerbaldi, M. 1997, A&A, 320, L29
- Cruz, K. L., Reid, I. N., Liebert, J., Kirkpatrick, J. D., & Lowrance, P. J. 2003, AJ, 126, 2421
- Freistetter, F., Krivov, A. V., & Löhne, T. 2007, A&A, 466, 389
- Ducati, J. R., Bevilacqua, C. M., Rembold, S. B., & Ribeiro, D. 2001, ApJ, 558, 309
- Galland, F., Lagrange, A.-M., Udry, S., et al. 2006, A&A, 447, 355
- Gratadour, D., Mugnier, L. M., & Rouan, D. 2005, A&A, 443, 357
- Heap, S. R., Lindler, D. J., Lanz, T. M., et al. 2000, ApJ, 539, 435
- Kalas, P., & Jewitt, D. 1995, AJ, 110, 794
- Lafrenière, D., Doyon, R., Marois, C., et al. 2008, ApJ, 670, 1367
- Lagrange, A.-M., Backman, D. E., & Artymowicz, P. 2000, Planetary Material around Main-Sequence Stars, in Protostars and Planets IV, ed. V. Mannings, A. P. Boss, & S. S. Russell (University of Arizona Press, Tucson), 639
- Leggett, S. K., Golimowski, D. A., Fan, X., et al. 2002, ApJ, 564, 452
- Lenzen, R., Hartung, M., Brandner, W., et al. 2003, SPIE 4841, 944
- Luhman, K. L., Wilson, J. C., Brandner, W., et al. 2006, ApJ, 649, 894
- Metchev, S., & Hillenbrand, L. 2006, ApJ, 651, 1166
- Mugnier, L. M., Fusco, T., & Conan, J.-M. 2004, JOSAA, 21, 1841
- Smith, B., & Terrile, R. 1984, Science, 226, 1421
- Marley, M. S., Fortney, J. J., Hubickyj, O., Bodenheimer, P., & Lissauer, J. J. 2007, ApJ, 655, 541
- Mayor, M., & Queloz, D. 1995, Nature, 378, 355
- Mouillet, D., Larwood, J. D., Papaloizou, J. C. B., & Lagrange, A.-M. 1997, MNRAS, 292, 896
- Okamoto, Y. K., Katata, H., Honda, M., et al. 2004, Nature, 431, 660
- Roussel, G., Lacombe, F., Puget, P., et al. 2003, SPIE 4839, 140
- Telesco, C. M., Fisher, R. S., Wyatt, M. C., et al. 2005, Nature, 433, 133
- van Dessel, E., & Sinachopoulos, D. 1993, A&AS, 100, 517
- Woodgate, B. E., Kimble, R. A., Bowers, C. W., et al. 1998, PASP, 110, 1183
- Zuckerman, B., Song, I., Bessel, M. S., & Webb, R. A. 2001, ApJ, 562, L87

## List of Objects

- ' $\beta$  Pictoris' on page 1
- 'HR 2435' on page 2
- '2M1207 b' on page 5
- 'AB Pic b' on page 5
- ' $\beta$  Pictoris b' on page 5