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A direct and differential imaging search for sub-stellar companions to ϵ Indi A ⋆ *(Research Note)*

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ABSTRACT

We have carried out a direct and differential imaging search for sub-stellar companions to ϵ Indi A using the adaptive optics system NACO at the ESO VLT. The observations were carried out in September 2004 with NACO/SDI as well as with NACO's S27 camera in the H and K_s filters. The SDI data cover an area of ∼2.8″ around ϵ Indi A. No detection was achieved in the inner neighbourhood down to 53 M_J (5 σ confidence level) at a separation ≥0.4″(1.45 AU) and down to 21 M_J for separations ≥1.3″ (4.7 AU). To cover a wider field of view, observations with the S27 camera and a coronagraphic mask were obtained. We detected a faint source at a separation of $(7.3 \pm 0.1)''$and a position angle of $(302.9 \pm 0.8)^\circ$. The photometry for the candidate companion yields $m_H = (16.45 \pm 0.04)$ mag and $m_{K_s} = (15.41 \pm 0.06)$ mag, respectively. Those magnitudes and the resulting color $(H - K_s) = (1.04 \pm 0.07)$ mag fit best to a spectral type of L5 – L9.5 if it is bound.
Observations done with HST/NICMOS by M. Endl have shown the source to be a background object.

Key words. stars: low-mass, brown dwarfs – stars: fundamental parameters

1. Introduction

At present, the nearby, high proper motion star ϵ Ind A has been a focus for studies about brown dwarfs and extrasolar planets for two different reasons. Firstly, since 2003 (Scholz et al. 2003) ϵ Ind A has been known to have a physical companion at a separation of ∼1500 AU which thereafter was found to be a binary consisting of two T dwarfs in the following named ϵ Ind Ba and Bb (Volk et al. 2003; McCaughrean et al. 2004). The two components have spectral types of T1 and T6 and estimated masses of 47 and 28 $M_{\rm Jup}$, respectively, assuming an age of 1.3 Gyr for the system. Dominated by the uncertainty in the age determination (possible range 0.8–2 Gyr; Lachaume et al. 1999), the uncertainties in the masses were calculated to be ≤25%. Secondly, Endl et al. (2002) reported the detection of a linear trend in the radial velocity measurements of ϵ Ind A. The observations were carried out with the ESO Coudé Echelle Spectrometer (CES) on La Silla. The best-fit to the RV measurements gives an RV shift of $+0.012 \pm 0.002$ ms^{-1} per day. The rms scatter around the slope is given as 11.6 ms^{-1}. Endl et al. (2002) considered that the linearity of the trend could be caused by a distant stellar companion as well as by a very long-period ($P > 20$ yrs) planetary companion. Our observations aimed at the direct detection of this companion.

Table 1. Parameters of ϵ Ind A.

Distance	(3.626 ± 0.009) pc
Spectral type	K4.5 V
Proper motion	∼4.7 as/yr
Age	∼1.3 Gyr
Age range	(0.8–2) Gyr
Mass	0.7 $M_\odot$
H magnitude	2.35 mag
K magnitude	2.24 mag

2. Observations and data reduction

2.1. Observation

In September 2004 observations of a sample of young, nearby stars were carried out at the VLT UT4 (Yepun) using the SDI (Simultaneous Differential Imager) mode of NACO. SDI has been implemented into CONICA (Lenzen et al. 2003) and has

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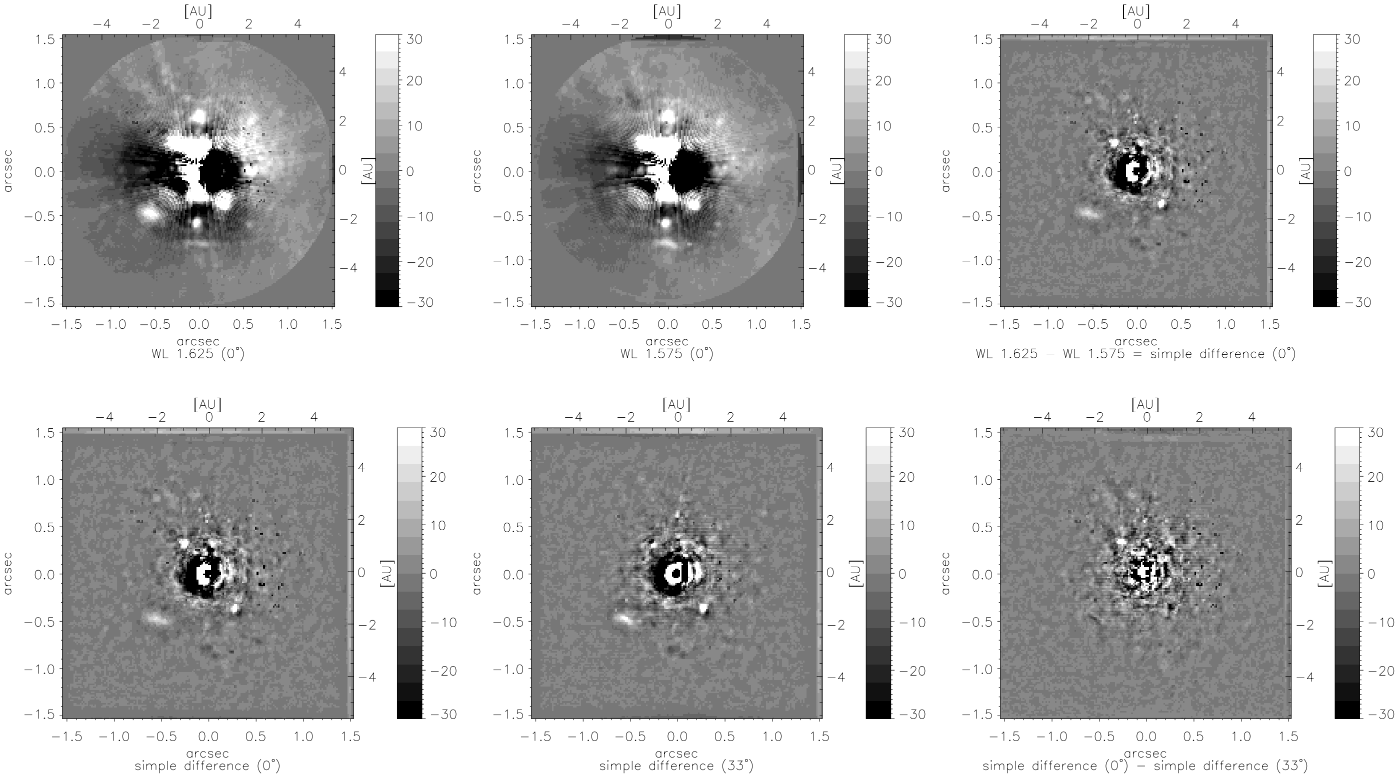

Fig. 1. SDI reduction sequence. *Upper panel*: images obtained in two different narrow band filters at the same rotator angle (here 0°) are subtracted to get a "simple difference" (at 0°). Note that from the left and middle image the respective symmetric radial profile was subtracted, to improve the visibility of the PSF noise. *Bottom panel*: two "simple difference" frames of different rotator angles (here 0° and 33°) are subtracted from each other to increase the contrast and to remove non common path aberrations.

been commissioned in August 2003 and February 2004. The special design of SDI allows simultaneous observations of four images through three narrow band filters, which are centered around the methane absorption band at 1.6 microns[1] (Lenzen et al. 2004). The image scale of the SDI camera is 17.25 mas/pixel and the total field-of-view (FOV) is 5″ × 5″, but due to the misalignment of the SDI field mask it was 2.7″ × 3.7″ at the time of our observations. For each star two SDI data sets were obtained at two rotator angles of 0° and 33°. ϵ Ind A was observed on September, 18. Per rotator angle 15 images were taken, each frame with a total integration time of $0.5\,\mathrm{s} \times 192 = 96\,\mathrm{s}$, resulting in a combined integration time of 24 min per observation angle. During the observations of ϵ Ind A the mean seeing was 1″ and the average Strehl ratio was 31%.

Due to the limited FOV and due to the knowledge of the radial velocity trend reported by Endl et. al. (2002) indicating a potential companion at large distances, additionally images with the NACO S27 objective were taken on September, 19. to cover a wider FOV. This objective has a FOV of 28″ × 28″ with a pixel scale of 27.03 mas/pixel. The observations were done in H and K_s, with ϵ Ind A masked out by a 1.4″ diameter coronographic mask. In each filter two images were obtained, each image with a total integration time of 120 s in H and 60 s in K_s, respectively.

2.2. SDI data reduction

The SDI data set has been reduced by an inhouse built data reduction pipeline optimized for NACO-SDI purposes. In a first step a standard reduction including flat fielding, sky-subtraction and badpixel mask multiplication is performed with each frame. Since each SDI raw frame contains four images of the star taken simultaneously in three narrow band filters (at 1.575 μm, 1.60 μm and 1.625 μm) the images are cut out and ordered according to their wavelength[2]. After rescaling them to a common λ/D platescale they are flux-calibrated. During the commissioning of the SDI camera, the optical distortion was shown to be less than 0.5% between and inside the given FOVs. Since the effect is very small we did not correct it. In the following all frames which belong to a certain wavelength are added with an accuracy of 0.1 pixel and averaged. In the next step the exact relative shift between the averaged frames of two different wavelength bands is calculated and thereafter the frames are subtracted to obtain a "simple difference" (see Fig. 1). For each star two SDI data sets with different rotator angles are obtained and separately reduced to obtain a "simple difference" frame for each rotator angles. The "simple difference" frames are in the following used to decrease non common path aberrations, which are still limiting the achieved contrast. While non common path aberrations artefact's are not affected by a rotation of the instrument, objects on sky rotate according to the specified angle. Therefore, non common path aberrations can be eliminated by subtracting two "simple difference" frames at different position angles of the detector. In the first place, to detect possible methane rich companions, we used the "simple difference obtained by subtracting the 1.625 μm from the 1.575 μm narrow band image, since a methane rich companion would be brightest in this difference image.

[1] The three narrow band filters are located at 1.575 μm , 1.60 μm and 1.625 μm.

[2] Two images are taken in the 1.625 μm filter, but one is too close to the edge of the detector and therefore not used.

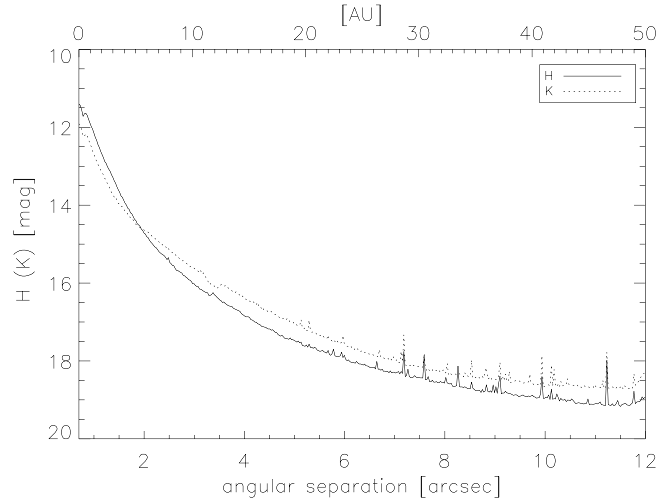

Fig. 2. 5σ detection limit for the NACO/S27 observations in H (full line, t = 120 s) and K_s (dotted line, t = 60 s). The region within a radius of 1″ from the star should be excluded since ϵ Ind A was masked out by a 1.4″ diameter coronographic mask and secondary the area around the coronographic mask is dominated by strong residuals.

2.3. NACO/S27 - wide field data

Common standard reduction steps like sky subtraction, flatfielding and bad pixel correction were applied to the data taken with the S27 camera. To obtain contrast curves for H and K_s (see Fig. 2) the standard deviation in dependence of the radial separation from ϵ Ind A was calculated.

3. Analysis

3.1. Detection limits for NACO/SDI

The wavelength bands of the SDI camera are centered around the methane absorption band at 1.6 microns, the three narrow band filters are located inside and outside the methane feature (1.575, 1.6, 1.625 μm). By subtracting the images of two different wavelength bands the flux of the central star cancels out, meanwhile the flux of a methane rich companion outside the absorption band remains ("simple difference") (Racine et al. 1999; Marois et al. 2000; Sparks & Ford 2002) . The two "simple difference" frames (one at 0° and one at 33°) are subtracted from each other, so that a methane rich companion would appear as a pair of positive and negative spots. In the completely reduced image of ϵ Ind A such a pair was not detectable. Figure 3 shows the detection limit obtained in the narrow band filter at 1.575 μm as well as in the "simple difference" image. To obtain the contrast curve, the standard deviation of the residuals was calculated as a function of radial distance from the star. Before comparing the observed magnitudes to evolutionary models to obtain a mass estimate, the observed detection limits have to be corrected for the offset between the SDI narrow band filters and the H band. This was done by Biller et al. (2006). The authors used the spectra of 15 objects with spectral types of T 4.5 – T7 and computed the expected H band magnitude as well as the narrow band magnitudes. From those magnitudes they obtained the offset between the filters for different spectral types. To obtain the mass estimate given in Fig. 3 we used the offset found for a spectral type of T5, which is (0.5 ± 0.05) mag and compared the final magnitude to the "COND"-models by Baraffe et al. (2003).

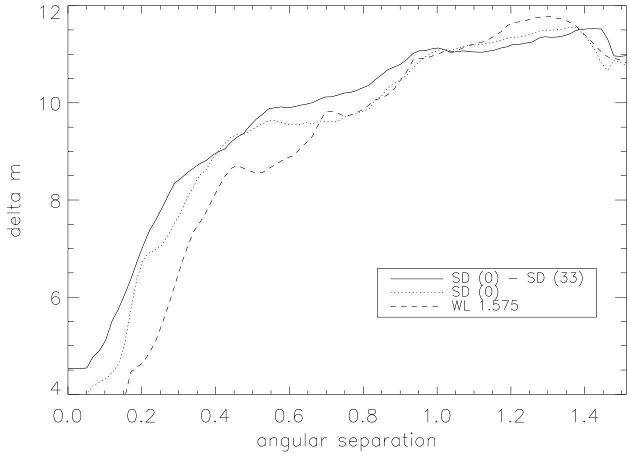

Fig. 3. The figure shows the 5 σ detection limits for ϵ Ind A in the narrow band filter at 1.575 μm, the "simple difference" (SD) at 0° and the detection limit after subtracting the two "simple difference" at 0° and 33° . In the finally reduced SDI images companions down to 21 M_J (5σ confidence level, system age of 1 Gyr) at separations greater than 1.3″ should be detectable.

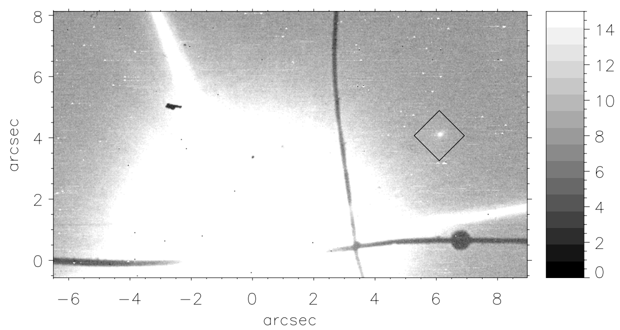

Fig. 4. Image of ϵ Ind A taken with NACO's S27 camera in K_s and ϵ Ind A masked-out. A faint source is visible on the upper right corner. It is (7.3 ± 0.1)″ away from the center and (302.9 ± 0.8)° from the north axis. North is up, East is left.

3.2. Candidate companion

In the data set obtained with NACO's S27 camera a faint source (see Fig. 4) at a separation of (7.3 ± 0.1) arcsec ((26.6 ± 0.5) AU) and a position angle of (302.9 ± 0.8)° was detected, with a S/N ratio greater than 25 in both filters[3]. The photometry was done with the IRAF APPHOT tool using as reference the standard star GSPC S279F. The apparent magnitudes for K_S and H are: $m_K = (15.41 \pm 0.06)$ mag and $m_H = (16.45 \pm 0.04)$ mag, respectively. An approximate spectral type for the candidate companion can be determined by comparing the $(H - K_s)$ color to the $(H - K)$ color of known brown dwarfs given by Leggett et al. (2002). The color fits best to a spectral type of L5–L9.

To verify whether the source is a physical companion or a background object we analysed older NICMOS data of ϵ Ind A taken in August 1997 with the NIC2 camera in the medium band filters *F180M*, *F207M* and *F222M*. In none of the images the source was detected.

New observations done on July, 18. 2005 by M. Endl with HST/NICMOS confute the companionship of ϵ Ind A and the candidate. The observations were carried out using the coronographic mode of the NIC2 camera and the *F160W* filter. ϵ Ind A

[3] To obtain the separation and the position angle of the source relative to ϵ Ind A, the pixelscale and N-orientation provided in the image header was used.

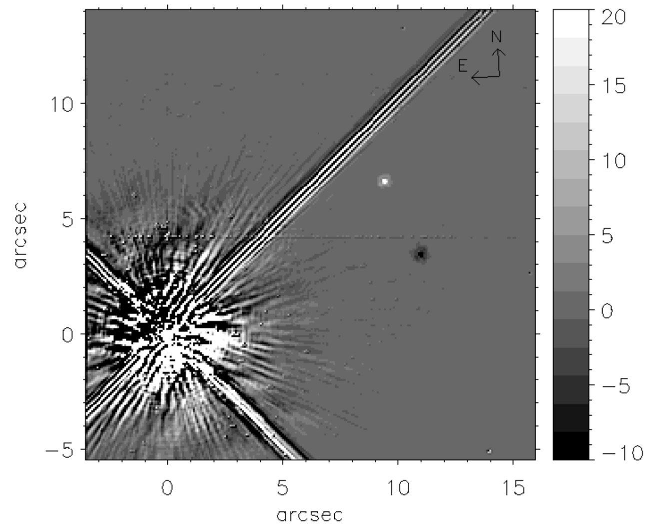

Fig. 5. HST/NICMOS observations from September,18. 2005. The observations were done in the F160W filter at two different rotator angles (86.8° and 104.8°) using the coronographic mode of the nic2 camera. Shown is the by 90° rotated difference image obtained after subtracting the two images of different rotator angles from each other. The former candidate is visible at a separation of $(11.3 \pm 0.2)''$. The north-east orientation is given for the positive source.

was observed at two different rotator angles (86.8° and 104.8°) with a total integration time of 299.1 sec at each angle. In both images the source is clearly visible at a separation of $(11.3 \pm 0.2)''$ from ϵ Ind A (see Fig. 5). In the 10 months between the VLT/NACO observations (Sep. 19, 2004) and the HST/NICMOS observations (July 18, 2005), ϵ Ind A moved by about $3.3''$ to the east, and $2.1''$ to the south (i.e. $3.9''$ in the direction PA = 122.6°). Hence the change in separations between the faint source and ϵ Ind A is entirely explained by the proper motion of ϵ Ind A. The position angle, however, remained almost constant as the direction of proper motion (122.6°) is almost perfectly along a line running through the faint source and ϵ Ind A. The source is definitely not co-moving with ϵ Ind A.

Table 2. Parameters of candidate.

	NACO/S27	NICMOS
Date of obs.	19.09.2004	18.07.2005
Separation ($''$)	7.3 ± 0.1	11.3 ± 0.2
Position angle (°)	302.9 ± 0.8	301.6 ± 1.8
H [mag]	16.45 ± 0.04	-
K [mag]	15.41 ± 0.06	-
F160W [mag]	-	16.93 ± 0.05

4. Conclusion

The SDI observations are basically limited by the rather old age of ϵ Ind A (compared to other SDI target stars), since the luminosity of sub-stellar companions strongly depends on the age of the system. Taking the COND models by Baraffe et al. 2003 to estimate the masses, candidates down to 21 $M_{\rm J}$ at separations $\geq 1.3''$(4.7 AU) should have been discovered.

The observations done with the NACO/S27 camera should have revealed objects with $K_{\rm s} < 15.6$ mag as well as $H < 16$ mag at separations $>3''$ from ϵ Ind A. When comparing these magnitude limits to the "COND"-models by Baraffe et al. (2003) a rough mass limit of $(16 \pm 4)\,M_{\rm J}$ can be derived.

The only candidate companion, which could be detected in the NACO/S27 observations, later on was revealed to be a background source by observations done with HST/NICMOS.

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