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Coronagraphic Search for Extra-Solar Planets around ϵ Eri and Vega [1]

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ABSTRACT

We present the results of a coronagraphic imaging search for extra-solar planets around the young main-sequence stars, ϵ Eri and Vega. Concentrating the stellar light into the core of the point spread function by the adaptive optic system and blocking the core by the occulting mask in the coronagraph, we have achieved the highest sensitivity for point sources in close vicinity of the both central stars. Nonetheless we had no confidential detection of a point source around the stars. The observations give the upper limits on the masses of the planets to $4 \sim 6$ Jupiter mass and $5 \sim 10$ Jupiter mass at a few arcsecond from ϵ Eri and Vega, respectively. Diffuse structures are also not detected around both stars.

Subject headings: stars: individual (ϵ Eri, Vega) — techniques: high angular resolution — planetary systems.

1. INTRODUCTION

Searches for extra-solar planets are very successful; over 180 planets have been discovered. However all discoveries so far were made using indirect methods, i.e. Doppler shift measurements and the transit method. Direct detection — imaging of the emission from an extra-solar planet — will open the door to investigating chemistry, meteorology, and biology under conditions completely different from those of the Earth and the other planets in the Solar System.

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[1]Based on data collected at the Subaru Telescope, which is operated by the National Astronomical Observatory of Japan.

The small angular separation between a planet and a central star and the huge difference in the brightness of the two objects make direct imaging difficult. The direct detection of extra-solar planets around pre-main sequence stars is less challenging in terms of the brightness difference, since young planets are bright in radiation. Itoh et al. (2005) discovered a young brown dwarf companion to the classical T Tauri star DH Tau, and the companionship was established by proper motion measurements. They derived the effective temperature by comparing its near-infrared spectrum with synthetic spectra of young low-mass objects (Tsuji et al. 2004). The mass is estimated to be 30 – 50 Jupiter mass (M_J) by comparison to evolutionary tracks (Baraffe et al. 2003; D'Antona et al. 1997) on the HR diagram. Chauvin et al. (2004) presented a direct image of a giant-planetary mass object around a young brown dwarf in the TW Hya association. Neuhäuser et al. (2005) announced the discovery of a proto-planet around GQ Lup. They estimated its mass to be 1 – 40 M_J using evolutionary tracks of Wuchterl et al. (2005) and Baraffe et al. (2003). However, in general, mass estimates of a proto-planet have large uncertainty. First, as pointed out by Itoh et al. (2005), determining the effective temperature by comparison of the spectrum to the spectra of field dwarfs tends to underestimate the value. Moreover, the evolutionary tracks of low-mass objects have large uncertainties. For example, we derive the mass of DH Tau B to be only 5 M_J, i.e. in the planetary mass range, if using the evolutionary track of Wuchterl et al. (2005). These two factors make it still unclear whether the low-luminosity companions are proto-planets.

Another approach to direct detection of extra-solar planets is, of course, detection of an extra-solar planet around a main-sequence star. Such an object does not have large ambiguities in the effective temperature estimate and in the mass estimate on the HR diagram. However, such an object is no longer bright in radiation. The flux ratio of the reflection light of a planet to a central star is described as $\frac{F_\mathrm{p}}{F_\mathrm{s}} = \frac{A}{2}(\frac{R_\mathrm{p}}{2a})^2$, where A, R_p, and a are albedo, the radius, and the semi-major axis of the planet, respectively. Reflection lights from all the extra-solar planets discovered by the Doppler shift measurements or the transit methods are difficult to be directly detected in reflected light, due to their faintness ($>$ 21 mag at the H-band) and/or due to their small separation ($< 0.3''$) from the star.

Alternative targets for direct detection are unknown extra-solar planets around nearby young main-sequence stars. Such planets are expected to be still bright in a contraction phase. Here we report the results of the coronagraphic observations of extra-solar planets around such young dwarfs, ϵ Eri and Vega. These stars are surrounded by dust rings, suggestive not only of their youths but also of the presence of a planet between the star and the ring.

2. TARGETS

2.1. ϵ Eri

ϵ Eri is the nearest young dwarf ($d \sim 3.3$ pc) with the indication of an extra-solar planet given by Doppler shift measurements (Hatzes et al. 2000). Amplitude of the Doppler shift is consistent with a planetary mass companion with $a = 3.4$ AU ($1\farcs0$). With its high chromospheric activities, ϵ Eri is believed to be young ($\sim$ 730 Myr; Song et al. 2000).

A clumpy debris disk is discovered around ϵ Eri in the submillimeter wavelengths (Greaves et al. 1998). The disk has a ringlike morphology with a peak at 60 AU ($18''$) from the central star and a cavity within 30 AU ($9''$). The inclination of the disk (i) is estimated to be $\sim 25°$. If the planet suggested by the Doppler shift measurement orbits coplanar with the debris disk, its mass is $\sim 2M_{\rm J}$. The H-band apparent magnitude of a 2 $M_{\rm J}$ planet is estimated to be 22.2 at 500 Myr and 25.4 at 1 Gyr (Baraffe et al. 2003).

The structure of the disk is also suggestive of the existence of a giant planet in orbit with moderate semimajor axis (40 $\sim$ 60 AU; Ozernoy et al. 2000; Quillen & Thorndike 2002). Kokubo & Ida (2002) predict that multiple giant planets may form in a moderate-mass disk if the disk has a long dissipation timescale. Both facts, that the circumstellar disk is long-lived and that a giant planet may orbit at 3.4 AU, imply the existence of other giant planets in the outer region.

The factors above combine to make ϵ Eri an attractive target for direct detection of an extra-solar planet.

2.2. Vega

The distance and age of this star are 7.76 pc and 350 Myr, respectively (Song et al. 2001). An extended circumstellar disk is found by sub-millimeter observations (Holland et al. 1998). It has two dust emission peaks at 60 AU ($8\farcs0$) and 75 AU ($9\farcs5$) from the central star. (Koerner et al. 2001; Wilner et al. 2002). From the dust distribution, Ozernoy et al. (2000) predicted a 2 $M_{\rm J}$ planet with the semi-major axis of 50 $\sim$ 60 AU. At the distance of Vega, the apparent H-band magnitude of a $2M_{\rm J}$ planet is estimated to be 19.2 and 24.1 for age of 100 Myr and 500 Myr, respectively (Baraffe et al. 2003).

Because of the pole-on geometry suggested by the circular symmetric structure of the dust and because of the spectral type of A0, a planet is difficult to be detected by Doppler shift measurements, if any.

3. OBSERVATIONS AND DATA REDUCTION

Because an extra-solar planet is thought to be faint and located in close vicinity of a bright central star, observations with high sensitivity and high dynamic range are strongly required. A stellar coronagraph with an adaptive optics system is one of the instruments suitable for such observations.

Coronagraphic observations of ϵ Eri and Vega were carried out on 2003 November 08 and 09 under fair condition with occasional cirrus. We used CIAO, which is equipped with a 1024×1024 InSb Alladin II detector with a spatial scale of $0\farcs0213$ pixel^{-1}. The observational band is the H-band. Because of the low effective temperature of a planet, we expect the thermal emission in the K-band to be suppressed below detection limit by atmospheric methane absorption. For example, the apparent K-band magnitude of a $5M_{\rm J}$ planet around ϵ Eri is estimated to be $22 \sim 26$ mag, several magnitude fainter than its H-band magnitude. The spatial resolution provided by the adaptive optics system was $0\farcs07$ (FWHM) for the natural seeing of $\sim0\farcs5$. The occulting masks were made of chrome on a sapphire substrate, within which the transmittance was a few tenths of a percent. This allowed us to measure the accurate position of the central object. Occulting masks with diameters of $1\farcs0$ and $2\farcs0$ were used for ϵ Eri and Vega, respectively. We used a traditional circular Lyot stop with its diameter 80 % of the pupil.

For taking images, we adjusted the telescope pointing finely so that the star was placed at the center of the occulting mask. Thirty exposures of 0.33 sec each were coadded into one frame. Both the telescope and the occulting mask were dithered by $\sim$ 1" every 40 minutes of integration time. The star was again placed at the center of the occulting mask, then additional frames were taken. The total integration times were 5.9 hour and 1.2 hour for ϵ Eri and Vega, respectively.

Given the limitations in observation time, we did not observe a reference star to determine the point spread function (PSF). As a photometric standard star, FS 4 was observed between the observations of Vega and ϵ Eri. Dark frames and dome flats with incandescent lamps were taken at the end of the night.

We observed both objects again on 2004 November 17 with the same configuration. Integration times for ϵ Eri and Vega were 3.5 hour and 12 min, respectively.

The Image Reduction and Analysis Facility (IRAF) was used for data reduction. A dark frame was subtracted from each object frame, then each object frame was divided by the dome-flat. Hot and bad pixels were removed from the frame.

We remove the halo of the central star in each image, by subtracting the rotated image of the object itself. The peak position of the PSF moved slightly on the detector during the observations. This was caused by the difference in the atmospheric distortion between the infrared wavelength at which the images were taken and the optical wavelength at which the wavefront was sensed. We measured the peak positions with the RADPROFILE task in IRAF and shifted the images to adjust the peak position to the center of the image. Then, each object frame was rotated by 180 degree. The peak position of the star in the rotated image was slightly adjusted so that its wing intensity level is the same as that of the original image in the region between $1\farcs3$ and $2\farcs1$ away from the peak. In this procedure, some frames were eliminated in which the AO compensation was poor. The halo of the star was suppressed in each frame after the rotated image was subtracted. Finally, all frames were combined into one image.

To detect companion candidates, we used the S-Extractor program with a 3σ detection threshold above the background. The extension of the background region strongly affects the source detection. We set 32 pixels and 64 pixels as the background mesh sizes, and an object was assigned to be detected if it was detected with both background sizes. We did not count the sources if the ellipticity of PSF calculated by the program was larger than 0.3 or if the semi-major axis of its PSF was larger than 3 pixels ($0\farcs064$). We also rejected the sources with semi-major axis smaller than 1 pixel ($0\farcs021$).

4. RESULTS AND DISCUSSION

4.1. ϵ Eri

An H-band coronagraphic image of ϵ Eri is presented in Figure 1. ϵ Eri, occulted by the mask, is located at the center, where the bright speckles display the residual halo of the PSF subtraction. Bright emissions located at the top and the right edge of the image are ghosts caused by a beam splitter and a compensator of the instrument. Another ghost at bottom-left to the central star is caused by the H-band filter.

We do not detect diffuse structures around the central star, whereas a part of the debris disk (Greaves et al. 1998) is located at the periphery of the field of view. Proffitt et al. (2004) estimated the surface flux of the disk to be $\sim 10^{-16}$ erg cm^{-2} s^{-1} arcsec^{-2} at the peak (55 AU) through optical to near-infrared region. This was consistent with the upper limit of the optical HST observations (Proffitt et al. 2004). Detection limit of our observation is 15.2 mag arcsec^{-2} in the region between $4''$(13 AU) and $10''$(33 AU) from the star, 4 orders of magnitude above the predicted flux from the dust.

One faint source is detected in close vicinity of the central star in our 2003 image. Its separation and position angle (PA) relative to the central star are 0.″91 and 144.°0. The source has the H-band magnitude of ~ 17.3 mag. We consider this source an artifact, since the residual halo of PSF subtraction is still dominant at 0.″9 from the central star. We think that the source is made by an azimuthally inhomogeneous profile of the PSF of the central star.

Otherwise, it may be an extra-solar planet. Base on the evolutionary track of low-mass objects (Baraffe et al. 2003), the source is estimated to have $6 \sim 8M_{\rm J}$, if it is associated with ϵ Eri. The separation of the source is not inconsistent with the planet suggested by Hatzes et al. (2000). As the planet was located near apoastron at the epoch of the 2003 observation, its separation from the central star is 4.86 AU (1.″5) at most. Since the planet moved away from its apoastron at the 2004 observation, it is located too close to the central star to be detected.

The source may be a background star, though a star count model of the Galaxy (Jones et al. 1987) shows that the expected number of background stars is only 0.01 within a 5" radius of ϵ Eri. Being located close to the Sun, ϵ Eri has very large proper motion (0.″977/yr with the PA of 271.°05). If the source observed in 2003 is a background star, it should be located at 1.″71 from the central star at the 2004 observations. But no object was identified there. Bright residual halo of PSF subtraction may prevent us from detecting the source.

We estimated the detection limit for a point source by adding pseudo-PSFs to the raw data. We made gaussian PSFs with 8.5 mag to 20.5 mag with 2 mag interval and 19.5 mag. Their FWHMs are 0.″075 (3.5 pixel). Then we placed them at 0.″5, 1.″0, 1.″5, and between 2.″0 and 10.″0 with 1.″0 interval from the central star. At each separation, the pseudo-PSFs are located at PA$= -90°$, $-45°$, $0°$, and $+45°$. When three or four PSFs at the same separation are identified by the S-Extractor program, it is assigned to be detected. The limiting magnitude is shown in Figure 2, as a function of the separation from the central star. At the region between $3''$ and $7''$ from the central star, the limiting magnitude is as deep as 18.5 mag at the H-band, corresponding to a $4 \sim 6M_{\rm J}$ planet at the same age of ϵ Eri. At the region beyond $7''$ from the central star, ghosts near the edges prohibit us from detecting faint sources. At the region within $2''$ from the central star, the detection sensitivity is severely restricted by the residual halo of the central star.

So far, our observation is the deepest search for extra-solar planets in the region between $3''$ and $7''$ from ϵ Eri. Several attempts have been made for direct detection of extra-solar planets around ϵ Eri. Macintosh et al. (2003) detected 10 faint objects at $17'' \sim 45''$away from ϵ Eri by K-band direct imaging observations. All are beyond the CIAO field of view. Their following proper motion measurements indicated that all the objects are background objects. While the limiting magnitude is about 21.5 mag (corresponding to 5 $M_{\rm J}$) beyond

15″ away from the star, the sensitivity is poor within 10″ from the star. One reason for such shallow limit is that they carried out direct imaging observations without any optics suppressing the brightness of the central star, such as an occulting mask.

Proffitt et al. (2004) found 59 faint objects in the region between 12.″5 and 58″ from ϵ Eri. Most of them are elongated, suggestive of background galaxies. They did not detect any object within our field of view. Though the detection limit of their observation is as deep as 26 mag in optical wavelengths, extra-solar planets are estimated to be orders of magnitude fainter in optical wavelengths than their detection limit.

Structure of the debris disk might be influenced by a planet. Quillen & Thorndike (2002) predicts a giant planet with a semi-major axis of 40 AU. Such a planet may be located beyond the CIAO field of view. Otherwise, a planet might be less massive. With an evolutionary track of Baraffe et al. (2003), a 1 $M_{\rm J}$ planet is expected to be as faint as 26 mag to 30 mag at the H-band. The negative result of our observation is therefore not inconsistent with their prediction.

4.2. Vega

An H-band coronagraphic image of Vega is presented in Figure 3. Vega, occulted by the mask, is located at the center. We do not detect any diffuse circumstellar structure, though two dust peaks identified by the sub-mm observations (Wilner et al. 2002) are located within the field of view of CIAO. Detection limit of our observation is 15 mag arcsec^{-2} around the dust peaks.

We do not detect any point source around the central star in both epochs. We estimate the detection limit for a point source by the same procedure we used for the ϵ Eri data (Figure 4). The limiting magnitude ($\sim$ 17 mag between 5″and 8″) is shallower than that for ϵ Eri. This is because integration time is shorter than that for ϵ Eri and Vega is much brighter than ϵ Eri. On the other hand, the detection limit in terms of mass is $5 \sim 10 M_{\rm J}$, similar to that of ϵ Eri, because Vega is younger than ϵ Eri.

A planet could induce inhomogeneity in the dust distribution. A planet, with Neptunian mass or several Jupiter mass, is predicted at 50 AU (6.″4) or 65 AU (8.″4) away from the central star (Ozernoy et al. 2000; Wilner et al. 2002; Wyatt et al. 2003). The negative result of our observation constrains the mass of the planet that they predict to less than $5 \sim 10 M_{\rm J}$.

An extra-solar planet around Vega has also been investigated. Macintosh et al. (2003) searched extra-solar planets also around Vega by direct imaging observations. Their K-band limiting magnitude was $\sim$ 20.5 mag beyond $20''$ from the central star, while only $\sim$ 17 mag ($6 \sim 12M_{\rm J}$) at $7''$from the central star. 7 objects were found $> 20''$away from the central star. Based on the proper motion measurements, they are thought to be background stars. Metchev et al. (2003) also investigated extra-solar planets around Vega. Their H-band limiting magnitude was about 19 mag ($2 \sim 6M_{\rm J}$) and 14 mag ($10 \sim 20M_{\rm J}$) at $20''$ and $7''$ from the central star, respectively. They detected 8 background stars.

Marois et al. (2006) observed Vega at 1.6 μm using the recently developed method for high contrast imaging. While their limiting magnitude reaches as deep as 20 mag at $8''$offset from the central star, they did not detect any faint object around Vega. Hinz et al. (2006) carried out M-band direct imaging observations of Vega. Using AO, they obtained diffraction-limited images with a detection limit of 7 $M_{\rm J}$ at $2\farcs5$ from the central star.

With a limiting magnitude that corresponds to $5 \sim 10M_{\rm J}$ in the region between $5''$and $8''$from the central star, our observations are so far one of the deepest search for an extra-solar planet around Vega,

5. CONCLUSIONS

We have carried out near-infrared coronagraphic observations of ϵ Eri and Vega. The observations are one of the deepest near-infrared searches for extra-solar planets in close vicinity of both central stars so far.

1. We did not detect any trustworthy point source around ϵ Eri. The upper limit on the mass of a planet is $4 \sim 6M_{\rm J}$ in the region between $3''$(10 AU) and $7''$(23 AU) from the star. Location of one point source candidate is not inconsistent with the planet suggested by the Doppler shift measurements. Another epoch observation will make it clear whether the candidate is a real object and whether it orbits ϵ Eri.

2. We did not detect any point source around Vega. Negative result of our observations puts an upper limit on the mass of a planet to $5 \sim 10M_{\rm J}$ in the region between $5''$(40 AU) and $8''$(60 AU) from the star.

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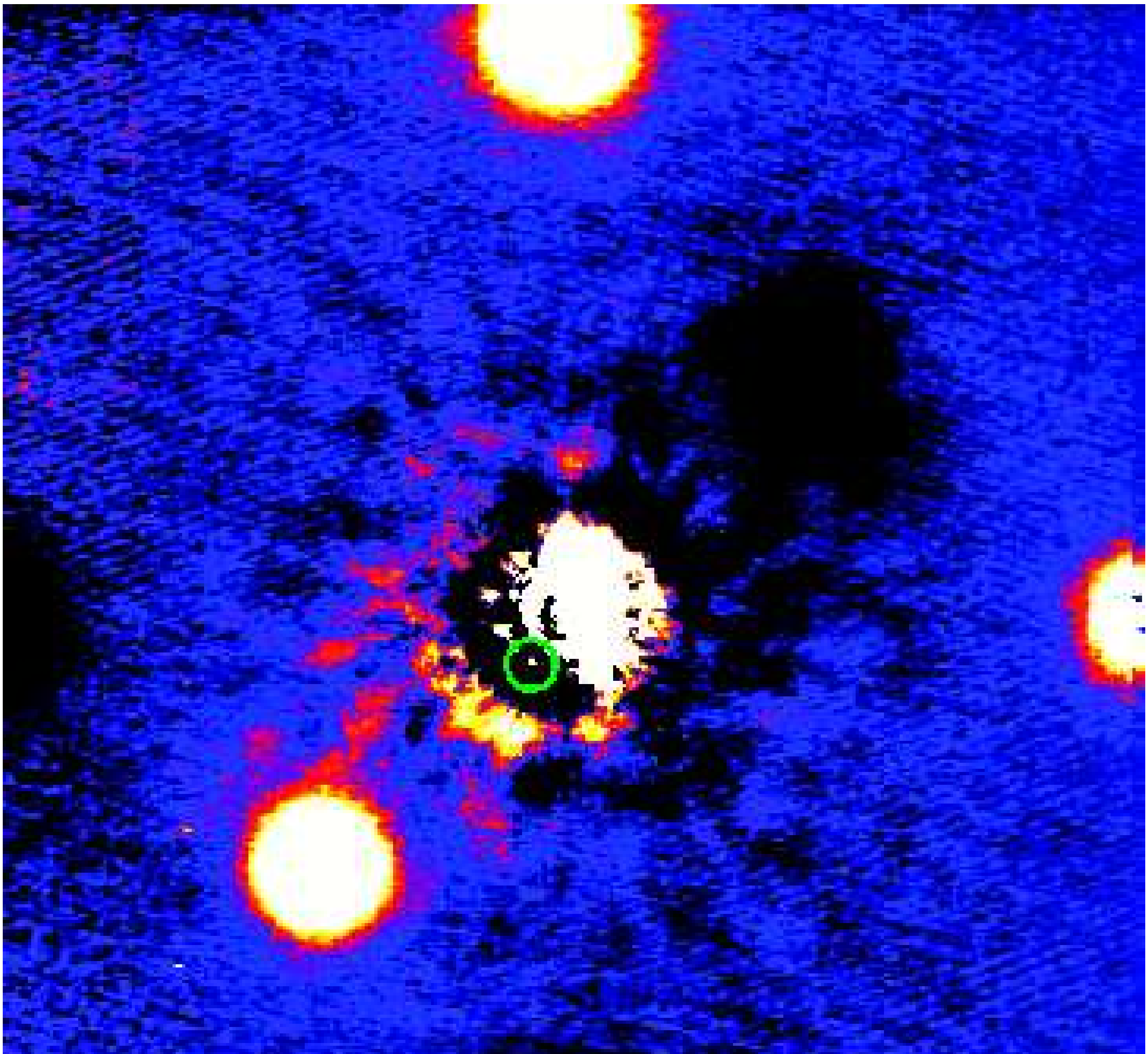

Fig. 1.— An H-band coronagraphic image of ϵ Eri taken during the 2003 observations presented here. North is up and east is to the left. The field of view is $19\farcs6 \times 20\farcs9$. The central star is located at the center of the image but is blocked by the mask. A residual halo from the PSF subtraction remains around the central star. The other 3 bright emissions are ghosts. The point source candidate is indicated by a green circle.

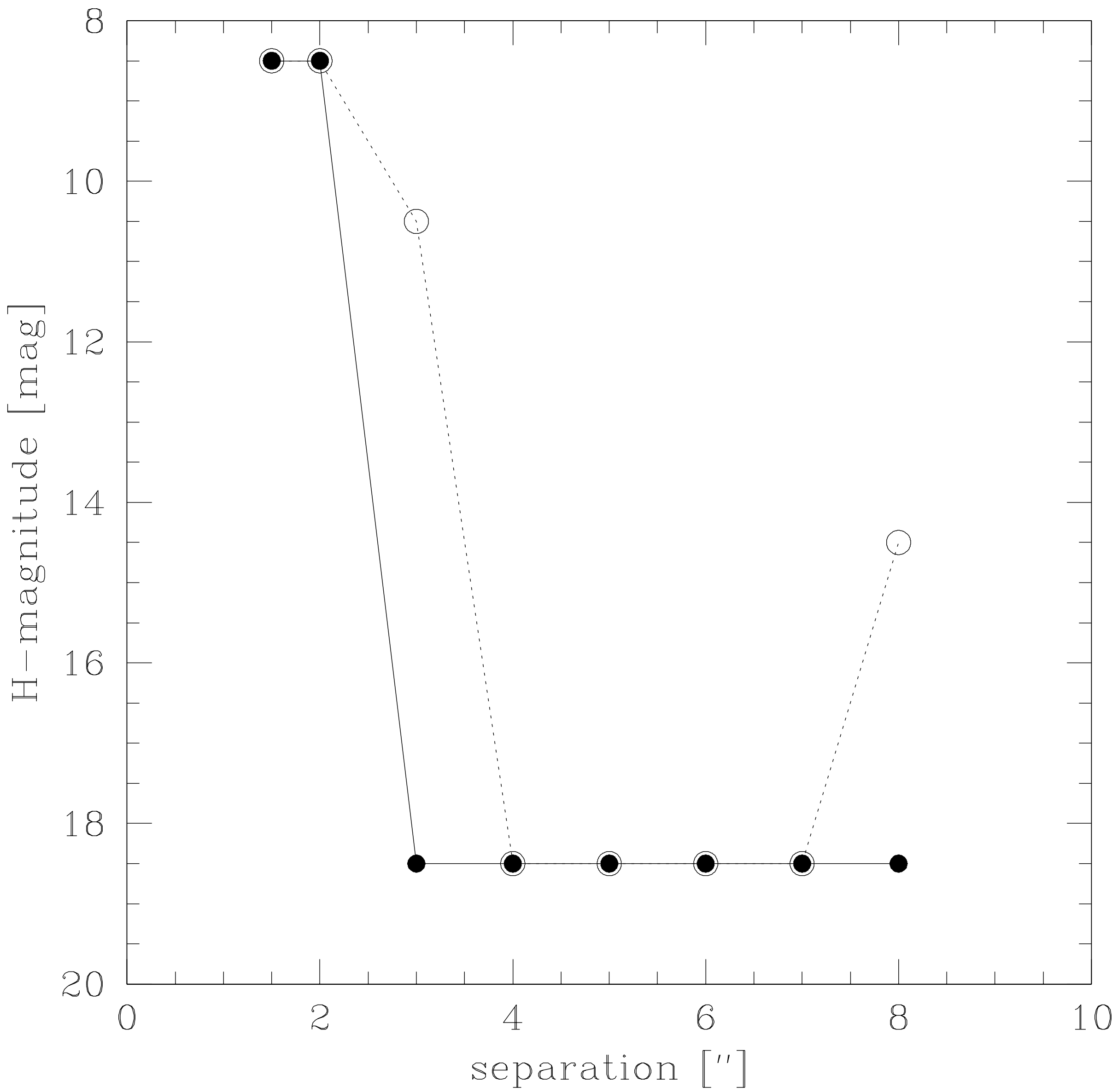

Fig. 2.— Limiting magnitude of the observation of ϵ Eri (filled circles for the 2003 observations, open circles for the 2004 observations). The limiting magnitudes are estimated by adding pseudo-stars. This observation is so far the deepest search for extra-solar planets at the region between 3″and 7″from the central star.

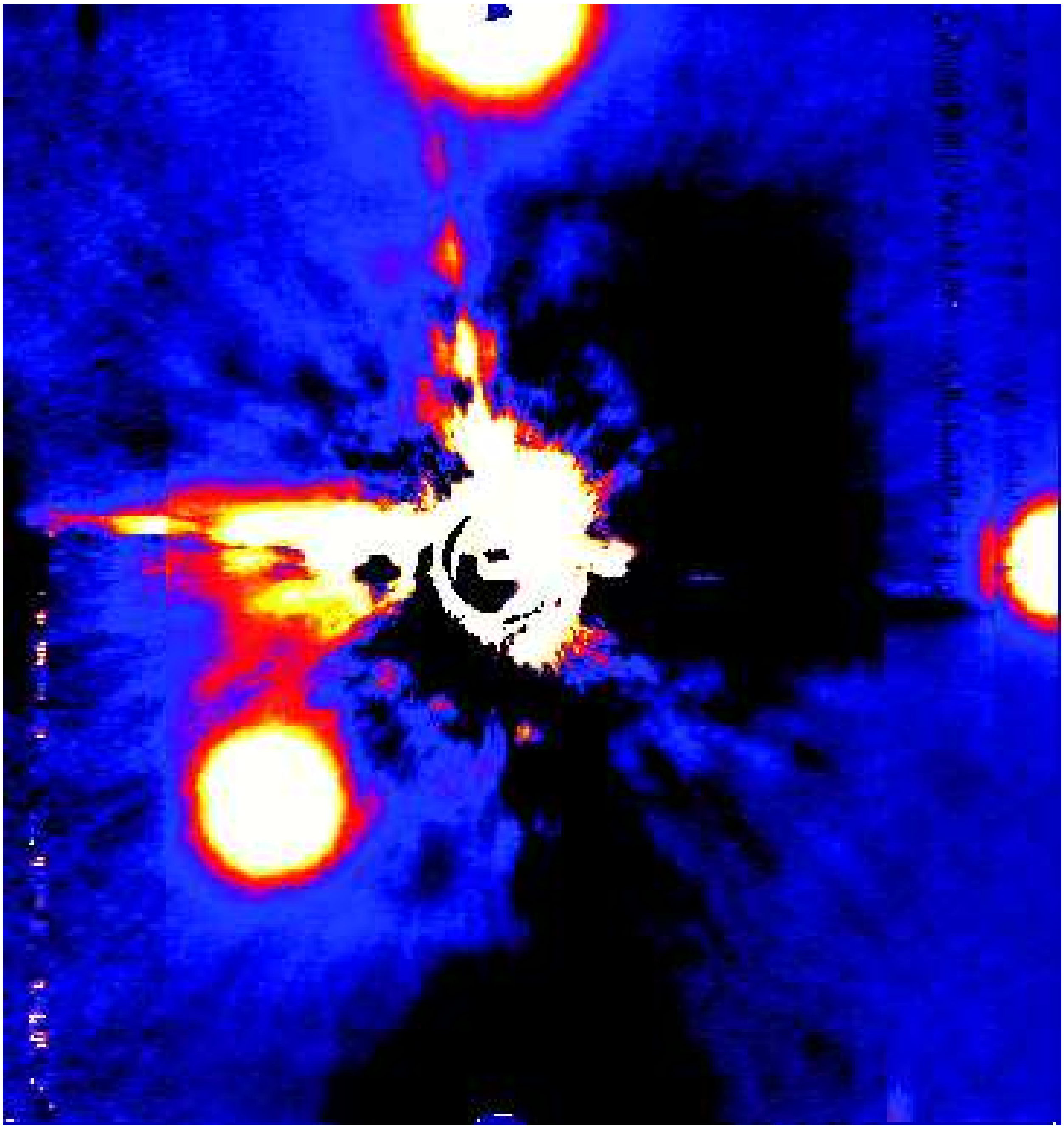

Fig. 3.— An H-band coronagraphic image of Vega taken during the 2003 observations. The field of view is $18''.9 \times 20''.2$. The star is located at the center of the image. The emission structures are residuals of the PSF subtraction, diffraction patterns of the spider, and ghosts. No stellar object was found around Vega.

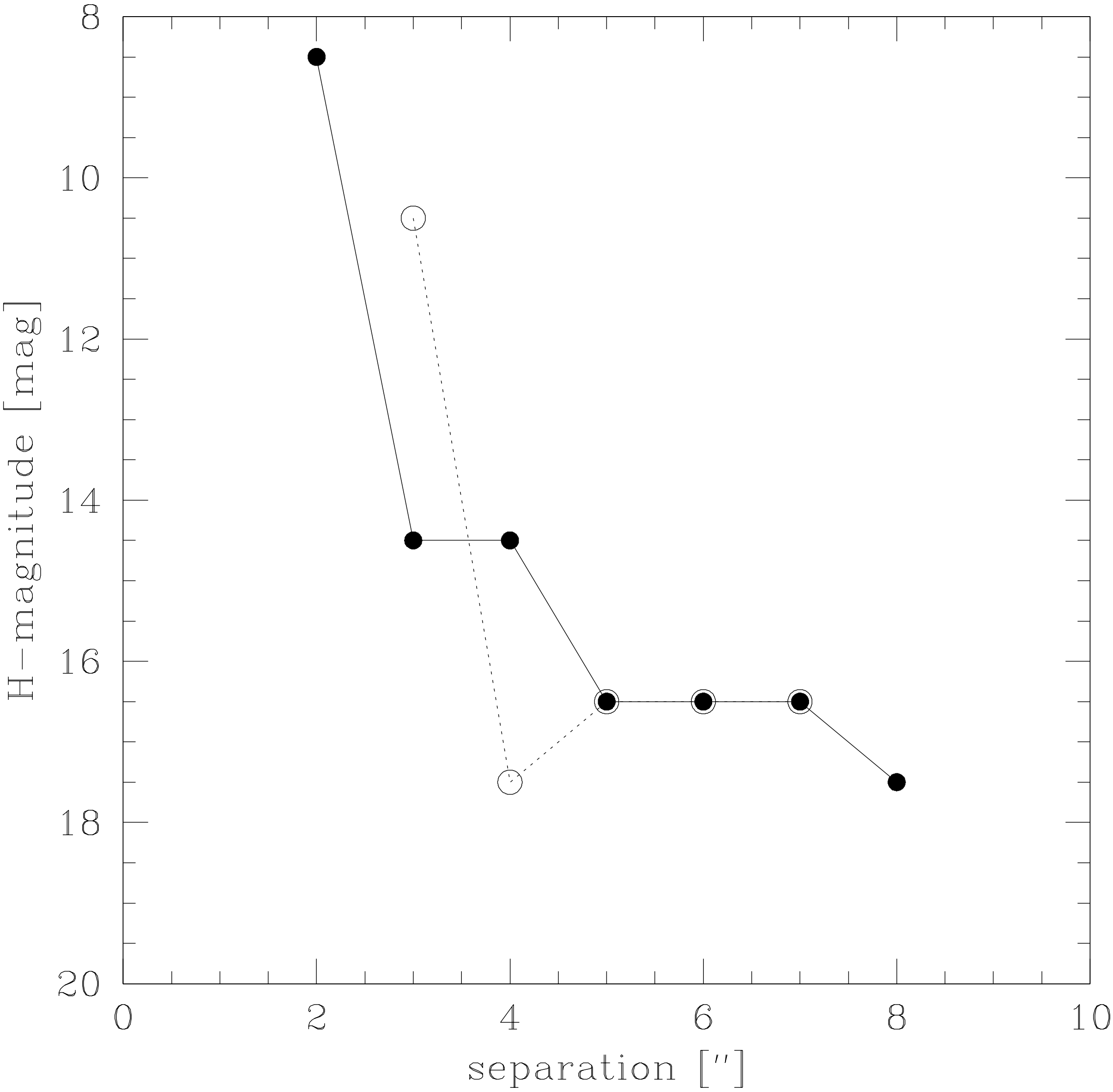

Fig. 4.— Limiting magnitude of the observation of Vega. The symbols are the same as in Figure 2. The limiting magnitudes are estimated by adding artificial PSFs.