CORONOGRAPHIC SEARCH FOR EXTRASOLAR PLANETS AROUND $\epsilon$ ERI AND VEGA$^1$

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ABSTRACT

We present the results of a coronagraphic imaging search for extrasolar planets around the young main-sequence stars $\epsilon$ 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 secure detection of a point source around the stars. The observations give the upper limits on the masses of the planets to $(4-6)M_J$ and $(5-10)M_J$ at a few arcseconds from $\epsilon$ Eri and Vega, respectively. Diffuse structures are also not detected around both stars.

Subject headings: planetary systems — stars: individual ($\epsilon$ Eri, Vega) — techniques: high angular resolution

1. INTRODUCTION

Searches for extrasolar 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 extrasolar planet—will open the door to investigating chemistry, meteorology, and biology in conditions completely different from those on the Earth and the other planets in the solar system.

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 extrasolar 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 association 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 $(30-50)M_J$ through comparison to evolutionary tracks (Baraffe et al. 2003; D’Antona & Mazzitelli 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 protoplanet around GQ Lup. They estimated its mass to be $(1-40)M_J$ using the evolutionary tracks of Wuchterl (2005) and Baraffe et al. (2003). However, in general, mass estimates of a protoplanet have a 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 $5M_J$, i.e., in the planetary mass range, when using the evolutionary track of Wuchterl (2005). These two factors leave it unclear whether the low-luminosity companions are protoplanets.

Another approach to direct detection of extrasolar planets is, of course, detection of an extrasolar planet around a main-sequence star. This kind of planet is not subject to 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 $F_p/F_a = A2(R_p/a)^2$, where $A$, $R_p$, and $a$ are albedo, the radius, and the semimajor axis of the planet, respectively. Reflected light from extrasolar planets discovered by the Doppler shift measurements or the transit methods is difficult to detect directly 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 extrasolar planets around nearby young main-sequence stars. It is expected that such planets are still bright as they remain in a contraction phase. Here we report the results of the coronagraphic observations of extrasolar planets around two such young dwarfs, $\epsilon$ Eri and Vega. These stars are surrounded by dust rings, suggestive not only of their youth but also of the presence of a planet between the star and the ring.

2. TARGETS

2.1. $\epsilon$ Eri

The object $\epsilon$ Eri is the nearest young dwarf ($d \sim 3.3$ pc) for which Doppler shift measurements indicate the presence of an extrasolar planet (Hatzes et al. 2000). The amplitude of the Doppler shift is consistent with a planetary mass companion with $a = 3.4$ AU (1”) with high values of chromospheric activity, $\epsilon$ Eri is believed to be young (~730 Myr; Song et al. 2000).

A clumpy debris disk has been discovered around $\epsilon$ Eri in the submillimeter wavelengths (Greaves et al. 1998). The disk has a ringlike morphology, with a peak at 60 AU ($18^\prime\prime$) from the central star and a cavity within 30 AU ($9^\prime\prime$). The inclination of the disk ($i$) is estimated to be $\sim25^\circ$. If the orbit of the planet indicated by the Doppler shift measurement is coplanar with the debris disk, its mass is $\sim2M_J$. The $H$-band apparent magnitude of a $2M_J$ 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 also suggests the existence of a giant planet in an orbit with a moderate semimajor axis (40–60 AU; Oszmer et al. 2000; Quillen & Thomdike 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 of these 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.

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These factors as discussed above combine to make $\epsilon$ Eri an attractive target for direct detection of an extrasolar planet.

2.2. Vega

The distance and age of this star are 7.76 pc and 350 Myr, respectively (Song et al. 2000). An extended circumstellar disk is found with submillimeter observations (Holland et al. 1998). It has two dust emission peaks, at 60 AU (83°) and 75 AU (97°) from the central star (Koerner et al. 2001; Wilner et al. 2002). From the dust distribution, Ozernoy et al. (2000) predicted a $2M_{\odot}$ planet with the semimajor axis of 50–60 AU. At the distance of Vega, the apparent $H$-band magnitude of a $2M_{\odot}$ planet is estimated to be 19.2 and 24.1 for an age of 100 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, it would be difficult to detect a planet by Doppler shift measurements, if indeed one is present.

3. OBSERVATIONS AND DATA REDUCTION

Because extrasolar planets are expected to be faint and located in the near vicinity of a bright central star, observations with high sensitivity and high dynamic range are very necessary. A stellar coronagraph with an adaptive optics (AO) system is one instruments that would be suitable for such observations.

Coronagraphic observations of $\epsilon$ Eri and Vega were carried out on 2003 November 8 and 9 under fair conditions, with occasional cirrus. We used the Coronagraph Imager with Adaptive Optics (CIAO), which is equipped with a 1024 InSb Alladin II detector with a spatial scale of 0.00213 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 the detection limit by atmospheric methane absorption. For example, the apparent $K$-band magnitude of a $5M_{\odot}$ planet around $\epsilon$ Eri is estimated to be 22 ~ 26 mag, several magnitudes fainter than its $H$-band magnitude. The spatial resolution provided by the AO system was 0.007 (FWHM) for natural seeing of ~0.5". The occulting masks were made of chrome on a sapphire substrate, within which transmittance was a few tenths of a percent. This allowed us to accurately measure the position of the central object. Occulting masks with diameters of 10" and 20" were used for $\epsilon$ Eri and Vega, respectively. We used a traditional circular Lyot stop with a diameter of 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 s each were co-added into one frame. Both the telescope and the occulting mask were dithered by ~1" every 40 minutes of integration time. The star was again placed at the center of the occulting mask, and then additional frames were taken. The total integration times were 5.9 and 1.2 hr for $\epsilon$ 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 $\epsilon$ 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 $\epsilon$ Eri and Vega were 3.5 hr and 12 minutes, respectively.

The Image Reduction and Analysis Facility (IRAF)$^4$ 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 removed 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 wave front was registered. We measured the peak positions with the RADPRFFILE 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°. The peak position of the star in the rotated image was slightly adjusted so that its wing intensity level would be the same as that of the original image in the region between 1.5" and 2.1" 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 SExtractor program with a 3 $\sigma$ 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 classified as detected if it was detected with both background sizes. We did not count the sources if the ellipticity of the PSF calculated by the program was larger than 0.3 or if the semimajor axis of its PSF was larger than 3 pixels (0.064). We also rejected the sources with semimajor axis smaller than 1 pixel (0.021).

4. RESULTS AND DISCUSSION

4.1. $\epsilon$ Eri

An $H$-band coronagraphic image of $\epsilon$ Eri is presented in Figure 1. The object $\epsilon$ Eri, occulted by the mask, is located at the

![Figure 1](image-url)
center, where the bright speckles show 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 $\sim 10^{-16}$ ergs cm$^{-2}$ s$^{-1}$ arcsec$^{-2}$ at the peak (55 AU) through the optical to near-infrared region. This was consistent with the upper limit of the optical Hubble Space Telescope observations (Proffitt et al. 2004). The detection limit of our observation is 15.2 mag arcsec$^{-2}$ in the region between 4" and 10" from the star, 4 orders of magnitude above the predicted flux from the dust.

One faint source is detected in near vicinity of the central star in our 2003 image. Its separation and position angle (P.A.) relative to the central star are 0\,\,91 and 144\,\,0. The source has an $H$-band magnitude of $\sim 17.3$ mag. We consider this source to be an artifact, since the residual halo of PSF subtraction is still dominant, at 0\,\,99 from the central star. We think that the source is made by an azimuthally inhomogeneous profile of the PSF of the central star.

If not, it may be an extrasolar planet. Based on the evolutionary track of low-mass objects (Baraffe et al. 2003), the source is estimated to be $(6-8)M_J$, if it is associated with $\epsilon$ 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 (1.75) 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, although a star-count model of the Galaxy (Jones et al. 1981) shows that the expected number of background stars is only 0.01 within a 5" radius of $\epsilon$ Eri. Located close to the Sun, $\epsilon$ Eri has very large proper motion ($0.977$ yr$^{-1}$ with the P.A. 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. A 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 defined Gaussian PSFs with 8.5 to 20.5 mag with 2 mag interval and 19.5 mag. Their FWHMs are $0.075$ (3.5 pixels). Then we placed them at $0.5, 1.0, 1.5, \ldots$ between 270 and 100, with a 10 interval from the central star. At each separation, the pseudo-PSFs are located at P.A. = $-90^\circ, -45^\circ, 0^\circ, +45^\circ$. When three or four PSFs at the same separation are identified by the SExtractor program, the object is classified as 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 $(4 \sim 6)M_J$ planet at the same age of $\epsilon$ 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 represents the deepest search for extrasolar planets in the region between 3" and 7" from $\epsilon$ Eri. Several attempts have been made for direct detection of extrasolar planets around $\epsilon$ Eri. Macintosh et al. (2003) detected 10 faint objects at $17'' \sim 45''$ away from $\epsilon$ Eri with $K$-band direct imaging observations. All are beyond the CIAO field of view. Their subsequent proper-motion measurements indicated that all the objects are background objects. While the limiting magnitude is about 21.5 mag (corresponding to 5$M_J$) beyond 15'' away from the star, the sensitivity is poor within 10'' from the star. One reason for such a shallow limit is that Macintosh et al. carried out direct imaging observations without any optics, such as an occulting mask, being used to suppress the brightness of the central star.

Proffitt et al. (2004) found 59 faint objects in the region between 12.5 and 58'' from $\epsilon$ Eri. Most of them are elongated, suggestive
of background galaxies. They did not detect any object within our field of view. Although the detection limit of their observation is as deep as 26 mag in optical wavelengths, extrasolar planets are estimated to be orders of magnitude fainter in optical wavelengths than their detection limit.

The structure of the debris disk might be influenced by a planet. Quillen & Thorndike (2002) predict a giant planet with a semi-major axis of 40 AU. Such a planet may be located beyond the CIAO field of view. Or it may be that the planet is less massive. With an evolutionary track of Baraffe et al. (2003), a 1 $M_J$ planet is expected to be as faint as 26 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, although two dust peaks identified with submillimeter observations (Wilner et al. 2002) are located within the field of view of CIAO. The 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 either epoch. We estimate the detection limit for a point source by the same procedure we used for the $\epsilon$ Eri data (Fig. 4). The limiting magnitude ($\sim$17 mag between 5$''$ and 8$''$) is shallower than that for $\epsilon$ Eri. This is because integration time is shorter than the one for $\epsilon$ Eri, and Vega is much brighter than $\epsilon$ Eri. On the other hand, the detection limit in terms of mass is (5–10)$M_J$, similar to that of $\epsilon$ Eri, because Vega is younger than $\epsilon$ Eri.

A planet could induce inhomogeneity in the dust distribution. A planet, of Neptunian mass or several Jupiter masses, 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 they predict to be less than (5–10)$M_J$.

The question of an extrasolar planet around Vega has also been investigated. Macintosh et al. (2003) also used direct imaging observations to search for extrasolar planets around Vega. Their $K$-band limiting magnitude was $\sim$20.5 mag beyond 20$''$ from the central star, but only $\sim$17 mag ([6–12]$M_J$) at 7$''$ from the central star. Seven 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 extrasolar planets around Vega. Their $H$-band limiting magnitudes were about 19 mag ([2–6]$M_J$) and 14 mag ([10–20]$M_J$) at 20$''$ and 7$''$ from the central star, respectively. They detected eight background stars.

Marois et al. (2006) observed Vega at 1.6 $\mu$m using the recently developed method for high-contrast imaging. While their limiting magnitude reaches as deep as 20 mag at an 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$M_J$ at 2.5$''$ from the central star.

With a limiting magnitude that corresponds to (5–10)$M_J$ in the region between 5$''$ and 8$''$ from the central star, our observations represent one of the deepest searches so far for an extrasolar planet around Vega.

5. CONCLUSIONS

We have carried out near-infrared coronagraphic observations of $\epsilon$ Eri and Vega. The observations represent one of the deepest near-infrared searches for extrasolar planets in close vicinity of both central stars so far.

1. We did not detect any trustworthy point source around $\epsilon$ Eri. The upper limit on the mass of a planet is (4–6)$M_J$ in the region between 3$''$ (10 AU) and 7$''$ (23 AU) from the star. The 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 $\epsilon$ Eri.

2. We did not detect any point source around Vega. The negative result of our observations puts an upper limit on the mass of a planet of (5–10)$M_J$ in the region between 5$''$ (40 AU) and 8$''$ (60 AU) from the star.

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REFERENCES

Baraffe, I., Chabrier, C., Barman, T. S., Allard, F., & Hauschildt, P. H. 2003, A&A, 402, 701

Chauvin, G., et al. 2004, A&A, 425, L29

D’Antona, F., & Mazzitelli, I. 1997, Mem. Soc. Astron. Italiana, 68, 807

Greaves, J. S., et al. 1998, ApJ, 506, L133

Hatzes, A. P., et al. 2000, ApJ, 544, L145

Hinz, P. M., et al. 2006, ApJ, in press

Holland, W. S., et al. 1998, Nature, 392, 788

—. 2005, ApJ, 620, 984

Jones, T. J., Ashley, M., Hyland, A. R., & Ruelas-Mayoroga, A. 1981, MNRAS, 197, 413

Koerner, D. W., Sargent, A. I., & Ostroff, N. A. 2001, ApJ, 560, L181
Kokubo, E., & Ida, S. 2002, ApJ, 581, 666
Macintosh, B., et al. 2003, ApJ, 594, 538
Marois, C., Lafrenière, D., Doyon, R., Macintosh, B., & Nadeau, D. 2006, ApJ, 641, 556
Metchev, S. A., et al. 2003, ApJ, 582, 1102
Neuhäuser, R., et al. 2005, A&A, 435, L13
Ozernoy, L. M., Gorkavyi, N. N., Mather, J. C., & Taidakova, T. A. 2000, ApJ, 537, L147
Proffitt, C. R., et al. 2004, ApJ, 612, 481
Quillen, A. C., & Thorndike, S. 2002, ApJ, 578, L149
Song, I., et al. 2000, ApJ, 533, L41
Tsuji, T., Nakajima, T., & Yanagisawa, K. 2004, ApJ, 607, 511
Wilner, D. J., et al. 2002, ApJ, 569, L115
Wuchterl, G. 2005, Astron. Nachr., 326, 905
Wyatt, M. C. 2003, ApJ, 598, 1521