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DEEP KECK ADAPTIVE OPTICS SEARCHES FOR EXTRASOLAR PLANETS IN THE DUST OF ϵ ERIDANI AND VEGA

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ABSTRACT

A significant population of nearby stars have strong far-infrared excesses, now known to be due to circumstellar dust in regions analogous to the Kuiper Belt of our solar system, although orders of magnitude more dense. Recent submillimeter and millimeter imaging of these systems resolves the circumstellar dust and reveals complex structures, often in the form of rings with azimuthal nonaxisymmetric variations. This structure might well be due to the presence of embedded brown dwarfs or planets. We have carried out deep adaptive optics imaging of two nearby stars with such asymmetric dust: ϵ Eri and Vega. Ten and seven candidate companions were seen in and near the dust rings of ϵ Eri and Vega, respectively, but second-epoch proper motion measurements indicate that all are background objects. Around these two stars we can thus exclude planetary companions at spatial scales comparable to the radius of the dust structures to a level of $M_K = 24$, corresponding to 5 Jupiter masses, for ϵ Eri, and $M_K = 19$–21, corresponding to 6–8 Jupiter masses, for Vega.

Subject headings: circumstellar matter — infrared: stars — planetary systems —
stars: individual (ϵ Eridani, Vega)

1. INTRODUCTION

The *IRAS* satellite discovered that a significant population of nearby main-sequence stars, including Vega, display strong excess far-infrared emission, now known to be due to circumstellar dust (Zuckerman 2001 and references therein.) The region containing the dust at these "Vega-like" stars is analogous to the solar system region associated with the Kuiper Belt, although the total dust mass is orders of magnitude higher than in our system. Recent submillimeter and millimeter imaging of these systems (Holland et al. 1998, 2003; Greaves et al. 1998; Koerner, Sargent, & Ostroff 2001; Wilner et al. 2002) resolves the circumstellar dust and reveals complex structures, often in the form of rings with azimuthal variations. This structure might be due to the presence of embedded brown dwarfs or planets (Liou & Zook 1999; Ozernoy et al. 2000; Kuchner & Holman 2002). Using the 10 m W. M. Keck II telescope, we have carried out deep near-infrared adaptive optics (AO) imaging of the regions near two stars with such asymmetric dust, ϵ Eri and Vega, to search for planetary companions responsible for the structure in the dust ring.

2. PROPERTIES OF THE TARGET STARS

The properties of the target stars are summarized in Table 1.

2.1. ϵ *Eri*

ϵ Eri is a particularly fascinating system from the standpoint of extrasolar planet detection. At 3.2 pc, it is one of the closest stars to Earth. ϵ Eri is thought to have a relatively young age of ~730 Myr (Song et al. 2000), and has a mass similar to that of our Sun. There is also tentative radial velocity evidence for a companion in an $a = 3.4$ AU orbit (Hatzes et al. 2000). These factors all combine to make it an attractive target for a sustained, deep imaging search for an extrasolar planet.

ϵ Eri's circumstellar dust was first resolved by Greaves et al. (1998). As the closest "dusty star," even the low resolution of SCUBA shows a well-defined ring structure with a radius of $20''$–$30''$ and apparently several dense regions. The presence of this considerable substructure suggests the possibility of an unseen agent, most likely a low-mass companion, shaping the dust. Simulations of the resonant structures in such a ring (e.g., Ozernoy et al. 2000; Liou & Zook 1999) indicate that, to produce such structures, a companion would have to be located not in the midst of the dust "lumps" but behind or ahead of them. *COBE* observations of zodiacal dust in our solar system show similar structures caused by the Earth (Reach et al. 1995). The modeling work does not constitute a unique solution, of course, so the best strategy is to completely image the circumstellar environment over a range of separations. ϵ Eri has a high proper motion ($\mathrm{PM_{RA}} \sim 1''\ \mathrm{yr}^{-1}$), so a single epoch of follow-up observations has allowed us to distinguish any true companion from a background object.

2.2. *Vega*

Vega, 8 pc from Earth, is the archetypal early-type infrared-excess star (Aumann et al. 1984). Submillimeter imaging (Holland et al. 1998) does not show a well-defined ring but instead two concentrations of emission at $10''$–$15''$. These could be either strong inhomegeneities in a face-on dust structure or the ends of a nearly edge-on ring; Vega itself is thought to be pole-on (Gulliver, Hill, & Adelman 1994.)

TABLE 1

Properties of Target Stars

Parameter	ϵ Eri	Vega
Spectral type	K2 V [a]	A0 V [a]
Distance (pc)..	3.22 [a]	7.76 [a]
V magnitude	3.73 [a]	0.03 [a]
K magnitude	1.62 [a]	−0.06 [a]
Age (Myr)	730 [b]	350 [c]
Proper motion (R.A., decl.) arcsec yr^{-1}	−0.98, 0.02 [a]	0.20, 0.29 [a]

[a] From the SIMBAD database.

[b] Song et al. 2000.

[c] Barrado y Navascues 1998, Song et al. 2001.

TABLE 2

UT Dates of Observations

Star	Field Offset (arcsec)	First Epoch	Second Epoch
ϵ Eri	24 E	2001 Dec 01	2002 Aug 20
ϵ Eri	24 S	2001 Dec 01	2002 Aug 20
ϵ Eri	24 W	2001 Dec 01	2002 Aug 21
ϵ Eri	24 N	2001 Dec 21	
Vega.............	center	2002 Feb 21	
Vega.............	5 N, 5 E	2002 Feb 21	
Vega.............	10 N, 10 E		2002 Aug 20

Millimeter interferometry (Koerner et al. 2001; Wilner et al. 2002) confirms the existence of these bright areas, with spectral properties consistent with warm dust. Modeling (Gorkavyi & Taidakova 2001; Wilner et al. 2002) shows that, as with ϵ Eri, this structure could be produced by a single planetary companion.

3. OBSERVATIONS

We observed both target stars with the NIRC2 camera and the facility AO system (Wizinowich et al. 2000a, 2000b) on the W. M. Keck II telescope. NIRC2 has a 1024 × 1024 pixel array and two main plate scales, $0\farcs01$ pixel^{-1} and $0\farcs04$ pixel^{-1}. Although the $0\farcs04$ pixel^{-1} scale marginally undersamples the typical K'-band image FWHM ($0\farcs06$), it is still a better choice for maximizing the (sensitivity × area) product than the oversampled $0\farcs01$ pixel^{-1} mode. This provides a field of view of $40''$ per image, corresponding to 130 AU at ϵ Eri and 320 AU at Vega.

ϵ Eri was first observed on 2001 December 1 and 21 (UT). We observed four fields, offset $24''$ north, south, east, and west from the star itself; this placed ϵ Eri off the array, minimizing ghost images and internally scattered light. The AO system remained locked on the $V = 3.7$ star, producing good AO correction (Strehl $\sim$0.4 at 2.1 μm). Although NIRC2 has a focal-plane coronagraph and selectable Lyot pupil stops, these modes had not been fully commissioned, and we did not use them for these observations.

At each position we obtained 15 K' (2.1 μm) images in a five-position dither pattern, each consisting of six co-adds of 15 s exposure, for a total of 22.5 minutes of integration. Since the edge of each image was dominated by bright scattered light from ϵ Eri itself, we had to obtain separate sky images, 10–15 images per target set, in positions offset by $600''$ from the star. Observations are summarized in Table 2, and Figure 1 shows the locations of the fields observed. Conditions were excellent and photometric for the December 1 observations, but somewhat nonphotometric (estimated at $\sim$1 mag extinction) during the December 21 observations covering the northern field.

Vega was observed in 2002 February (see Table 2). Since the angular extent of the dust structures near Vega is smaller than the dust extent at ϵ Eri and the Vega dust is asymmetric, we observed only two positions: one centered on Vega, with the star placed behind a $2''$ diameter partially transparent occulting spot, and one offset $5''$ north and east, covering the regions where the dust is densest. The pointing centered on Vega probes a physical scale (<160 AU) similar to the four ϵ Eri images, and the offset image provides additional phase space in the direction where the dust is denser, although of course a perturbing planet need not be located inside the dust itself. The observations were otherwise identical to those taken of ϵ Eri, with 15 × 6 × 15 s of total exposure per position. Sensitivity was similar in both the

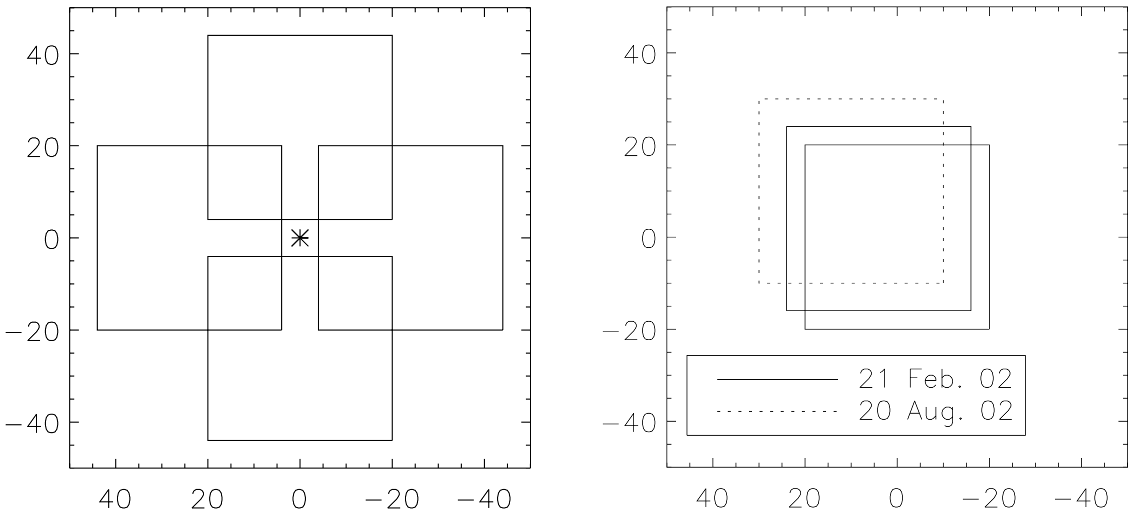

Fig. 1.—Field of view of the four ϵ Eri images (*left*) and three Vega images (*right*). Axes are in arcseconds.

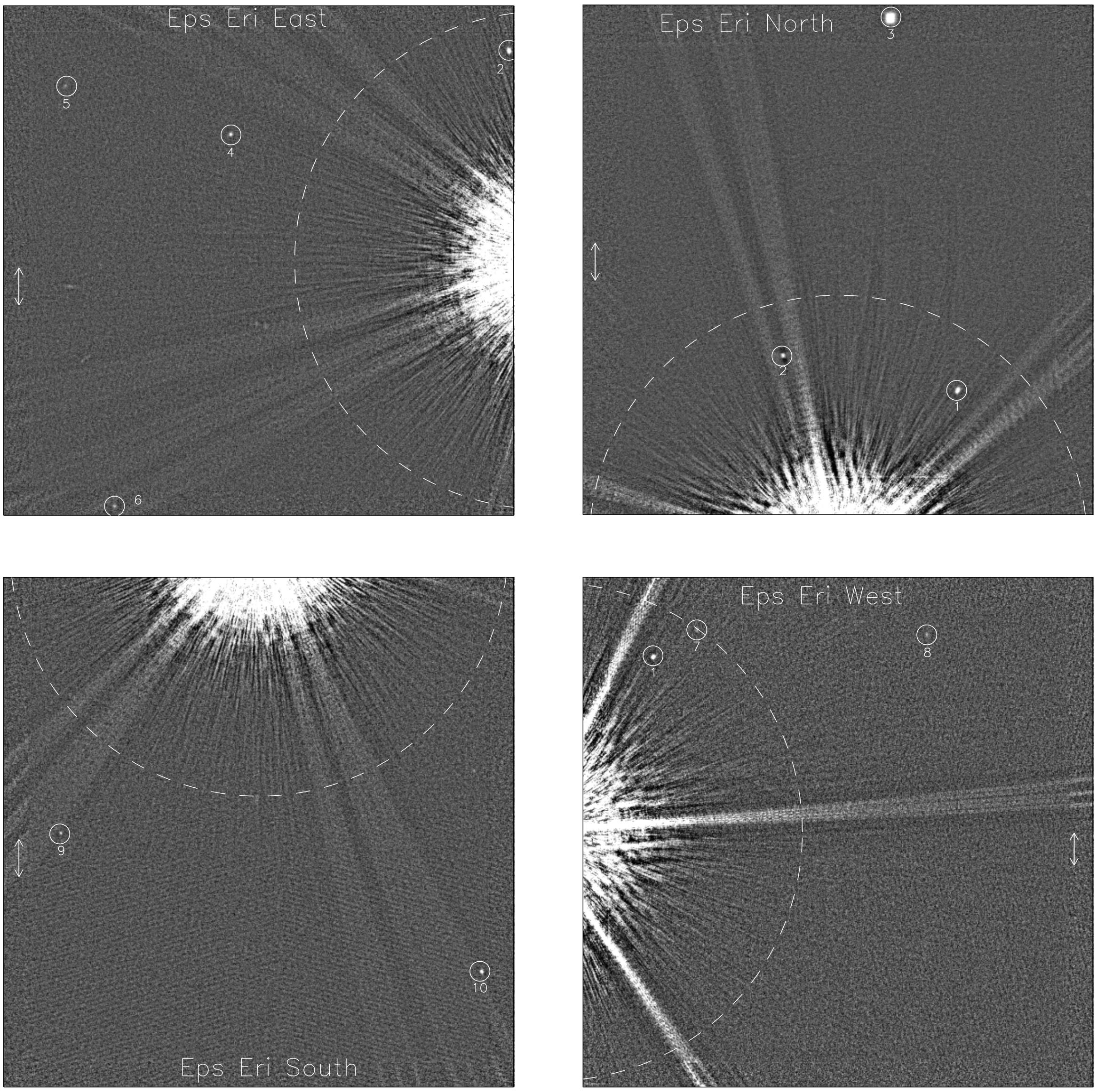

FIG. 2.—Deep NIRC2 K' images of ϵ Eri, offset 24″ east (*top left*), north (*top right*), south (*bottom left*), and west (*bottom right*) from the star. The dashed line indicates a radius of 20″ from the primary star, and the arrow a length of 3″. Candidate companions (all now known to be background objects) have been circled.

centered image and the offset image; the occulting spot by itself provided no significant rejection of scattered light. This is unsurprising, since the main source of the scattered light halo at these large radii is residual atmospheric or telescope phase errors uncorrected by the adaptive optics system rather than diffraction.

The dust rings themselves are, unsurprisingly, invisible in these near-infrared images. The total optical depth in dust near Vega is more than an order of magnitude lower than that of dust disks that have been detected in scattered light, such as β Pictoris. In addition, AO observations are ill suited to circumstellar dust detection. Adaptive optics only reduces light scattered by the atmosphere at separations less than $\sim\lambda/d$ (where d is the subaperture size of the AO system), which is $\sim 0\farcs7$ for the Keck AO system. Beyond this radius the scattered light halo is essentially the same as in a non-AO observation. Although AO can still provide enormous gains in point-source sensitivity by concentrating the light of a possible companion into a diffraction-limited spike, it provides insignificant enhancement to sensitivity to diffuse circumstellar emission. Thus, although our sensitivity to point sources is considerably greater than the NICMOS observations of Silverstone, Schneider, & Smith (2002), our sensitivity to diffuse emission is actually less.

Ten point sources were detected near ϵ Eri and seven near Vega. Both stars were reobserved in 2002 August. Total exposure times were the same; data obtained on August 20 were near-photometric, data from August 21 of somewhat lower quality. Because of poor conditions we were unable to reobserve the northern ϵ Eri offset field. Only one source in this field is not in the region of overlap with the eastern and western fields, and that source is near the northern edge of the northern field and hence highly unlikely to be a companion. All other sources detected in the first-epoch images were redetected in the second. The second-epoch observations of Vega are offset farther north and east than the first-epoch and detect a new source near the eastern edge, but this is again unlikely to be a true companion.

4. DATA ANALYSIS AND RESULTS

Images were dark-subtracted, sky-subtracted, and flat-fielded with standard infrared astronomical techniques. Dithered images in each field were registered by measuring the positions of point sources present in them, and median-combined to reject artifacts and ghosts. The images were then processed with an "unsharp mask," by subtracting a median-smoothed version of the image from itself; this has the effect of removing any smooth scattered light background and highlighting point sources.

We then identified and measured the positions of all the apparently pointlike sources in each field. All of the objects seen in the field appear to be point sources within the resolution of the AO system (~0″.1, including undersampling and isoplanatism effects.)

Figures 2 and 3 show the images with the point sources numbered. We measured approximate offsets from the (highly saturated) image of the primary star or the point of intersection of the diffraction spikes, but for astrometric purposes we measured the offsets of the point sources relative to the brightest source in each field, rather than to the primary, which was typically off the field or saturated. In the second-epoch images, each target was reidentified and its position remeasured. Tables 3 and 4 summarize the positions of the identified point sources and their change in position since the first epoch. Distortions in the camera were corrected using the equations given in the NIRC2 pre-ship review;[1] these were not significant for ϵ Eri, for which each field was observed in the same orientation in each epoch, but were significant for Vega, for which the Keck image rotator was oriented differently during the second epoch. Based on measurements of relative positions of the brightest sources in multiple images, the expected uncertainty in the relative astrometry is estimated to be ±0″.03.

Since it is highly unlikely that all objects would be planetary companions, by using the brightest object in each field as a reference grid, we would expect to measure a change in position equal to the proper motion of the primary star; in fact, within the errors, no candidates changed their relative positions. Vega source 7 changed position at the 3 σ level, but not in the direction expected for a true companion. This source is located near the edge of the image and may be subject to residual distortion effects.

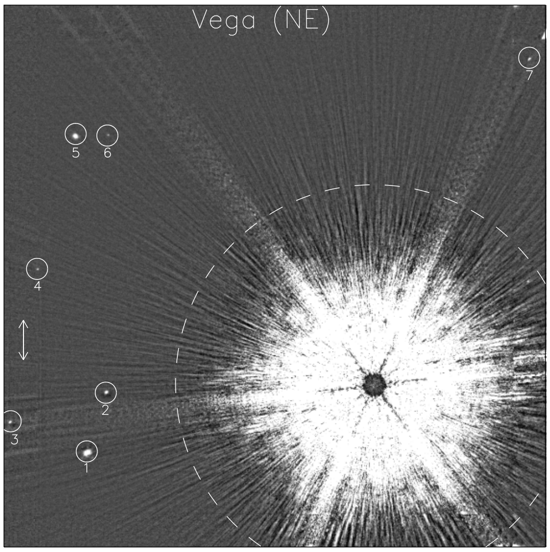

Fig. 3.—Deep NIRC2 image of the second-epoch field around Vega, offset 10″ north and east of the primary star. All candidate companions seen near Vega are visible in this field. The dashed line indicates a radius of 15″ from the primary star, and the arrow a length of 3″.

We performed coarse aperture photometry of our targets. Aperture photometry on images of the star HD 77281 were used for absolute calibration, with an 0″.8 radius aperture, large enough that variations in AO performance will not affect the photometric zero point (although variations in seeing could still change the calibration.) HD 77281 is sufficiently bright ($V = 7$) that AO performance was

TABLE 3

Candidate Companions near ϵ Eri

Object	Offset R.A. from Primary (arcseconds)	Offset Decl. from Primary (arcseconds)	Astrometric Reference	ΔR.A.	ΔDecl.	$m_{K'}$
Expected motion of a true companion......................				−0.704	0.014	
1......................	−9.6	14.2	ref for N, W	ref	ref	17.3
2......................	4.5	17.0	ref for E	ref	ref	17.3
3......................	−4.2	44.1	1	[a]	[a]	16.3
4......................	26.8	10.3	2	−0.009	0.018	19.4
5......................	38.7	14.5	2	0.018	0.096	20.7
6......................	36.1	−19.6	2	0.032	−0.01	20.2
7......................	−13.1	16.4	1	0.016	0.056	20.3
8......................	−31.2	13.6	1	0.026	0.001	20.1
9......................	15.9	−22.9	9	−0.033	0.02	20.8
10....................	−17.8	−34.1	ref for S	0.020	0.033	19.3

Note.—Offset R.A. and decl. are offsets from primary star in the first measurement epoch. Typical errors are ±0″.2, dominated by uncertainty in the position of the primary star. Astrometric reference indicates either the field for which the star was used as a reference or the candidate used for the measurements of the change in position between the two epochs. ΔR.A. and Δ DEC indicate the change in relative position of the candidate between the two epochs. Uncertainties in ΔR.A. and Δdecl. are 0″.02. The m_K gives an approximate apparent K magnitude; errors (mainly due to uncertainties in the quality of AO correction and in isoplanatic effects) are ±0.3.

[a] No observations in second epoch.

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[1] See http://alamoana.keck.hawaii.edu/inst/nirc2/preship/preship_testing.ps.

TABLE 4

Candidate Companions near Vega

Object	Offset R.A. from Primary (arcsec)	Offset Decl. from Primary (arcsec)	Astrometric Reference	ΔR.A.	ΔDecl.	m_K
Expected motion of a true companion.......................				0.098	0.143	
1.......................	21.6	−5.0	ref. for all	. . .	. . .	14.9
2.......................	20.2	−0.5	1	−0.027	0.020	17.2
3.......................	27.5	−2.9	n/a	[a]	[a]	18.5
4.......................	25.5	8.8	1	−0.005	0.028	19.4
5.......................	22.6	18.8	1	0.012	0.038	16.3
6.......................	20.1	18.9	1	0.023	0.052	20.5
7.......................	−11.9	24.6	1	0.110	0.008	18.3

Note.—Offset R.A. and decl. are offsets from primary star in the first measurement epoch. Typical errors are $\pm 0\farcs2$, dominated by uncertainty in the position of the primary star. Astrometric reference indicates either the field for which the star was used as a reference or the candidate used for the measurements of the change in position between the two epochs. ΔR.A. and Δ decl. indicate the change in relative position of the candidate between the two epochs. Uncertainties in ΔR.A. and Δdecl. are $0\farcs02$. The m_K gives an approximate apparent K magnitude; errors (mainly due to uncertainties in the quality of AO correction and in isoplanatic effects) are ±0.3.

[a] No observations in first epoch.

comparable to that on ϵ Eri or Vega. We then used the same aperture to measure the brightness of source 2 in the ϵ Eri images. Relative photometry for all the sources was determined using the unsharp-mask images (to remove the effects of diffuse background light from the primary star) and $0\farcs12$ radius apertures, with the calibration tied to the measurement of source 2. Since the differences between the point-spread function of the AO system during ϵ Eri and photometric standard observations are unknown, and since isoplanatic effects may further reduce the Strehl ratio at large radii, the relative accuracy between different companions (especially those at similar radii) should be good, but with ±0.3 mag of error in absolute calibration. For Vega, we followed a similar procedure using source 1.

Our data can be used to set upper limits on planetary companions near these stars. We measured the noise in an image at a given radius by calculating the standard deviation in narrow annuli, scaled to the size of our photometric apertures and compared to an estimate of the flux in the core of the AO PSF from the photometric calibration discussed above. The resulting 5 σ limiting magnitude is shown in Figure 4. Except for the large diffraction spikes (which are partially removed through combination of multiple images) our images are relatively uniform (sensitivity does not vary as a function of azimuth), although sensitivity is significantly lower in the northern offset field of ϵ Eri because of poor conditions. The Vega sensitivity limits come from the offset image, which has comparable sensitivity as a function of radius to the centered image. These can be compared to the predicted brightness of extrasolar planets from models (Burrows et al. 1997; Burrows 2002; Marley et al. 2002.) We could detect a 4–5 Jupiter mass planet at the separation of the ϵ Eri dust ring and a 6–8 Jupiter mass planet at the separations of the Vega dust structure.

It is interesting to compare our results to those of Metchev, Hillenbrand, & White (2003), who observed Vega with the Palomar AO system (PALAO). Our sensitivity is 2–3 mag greater, but in terms of detectable companion mass is roughly comparable to what they claim. This is largely because they have observed at the H band; brown dwarf models predict extremely blue $H-K$ colors, such as −2.1 for a $T_{\rm eff} = 450$ K 6 Jupiter mass object at the age of Vega (Burrows et al. 1997). However, factors such as clouds (Marley et al. 2002) can operate to bring objects closer to blackbody spectra; for observed brown dwarfs, clouds do not seem to be significant below $T_{\rm eff} = 1200$ K, but for lower gravity objects such as planets their strength is unknown. If clouds are significant, the $H-K$ colors of planets would be redder, and hence our mass limits would be lower than those of Metchev et al. (2003). Since the properties of planetary-mass objects in this temperature range are unknown, observing at a range of different wavelengths may be a sensible strategy, and the data of our two groups may complement each other.

Over the overlap between our fields and those of Metchev et al. (2002), we detect all sources in their images; our source 4 is in their field but below their sensitivity limit. Our photometry, although crude, systematically disagrees with theirs by approximately 0.5 mag. Absolute adaptive optics photometry is notoriously difficult, so this could be due to differences in AO performance between their photometric calibration and Vega observations. Their seeing was described as mediocre and variable ($0\farcs7$–$1\farcs0$ in H), and they used a $V = 10$ calibrator, which might cause significantly worse AO performance for an AO system with small subapertures such as PALAO. McCarthy (2001) used conventional near-IR imaging to search for substellar companions to young stars, and also observed Vega in conjunction with Holland et al. (1998). Although direct imaging is much less sensitive than AO imaging it is also photometrically easier to calibrate, and our photometry for the brightest sources near both Vega and ϵ Eri is consistent with that of C. McCarthy (2002, private communication), who measured $m_K = 15.0$ for our Vega source 1 and $m_J = 18.1$ for our ϵ Eri source 2.

5. CONCLUSIONS

Deep AO imaging of fields around ϵ Eri and Vega show no evidence of brown dwarf or planetary companions that could be confining or shaping the dust ring, down to the 5 Jupiter mass level (ϵ Eri) and 6–8 Jupiter mass level (Vega)

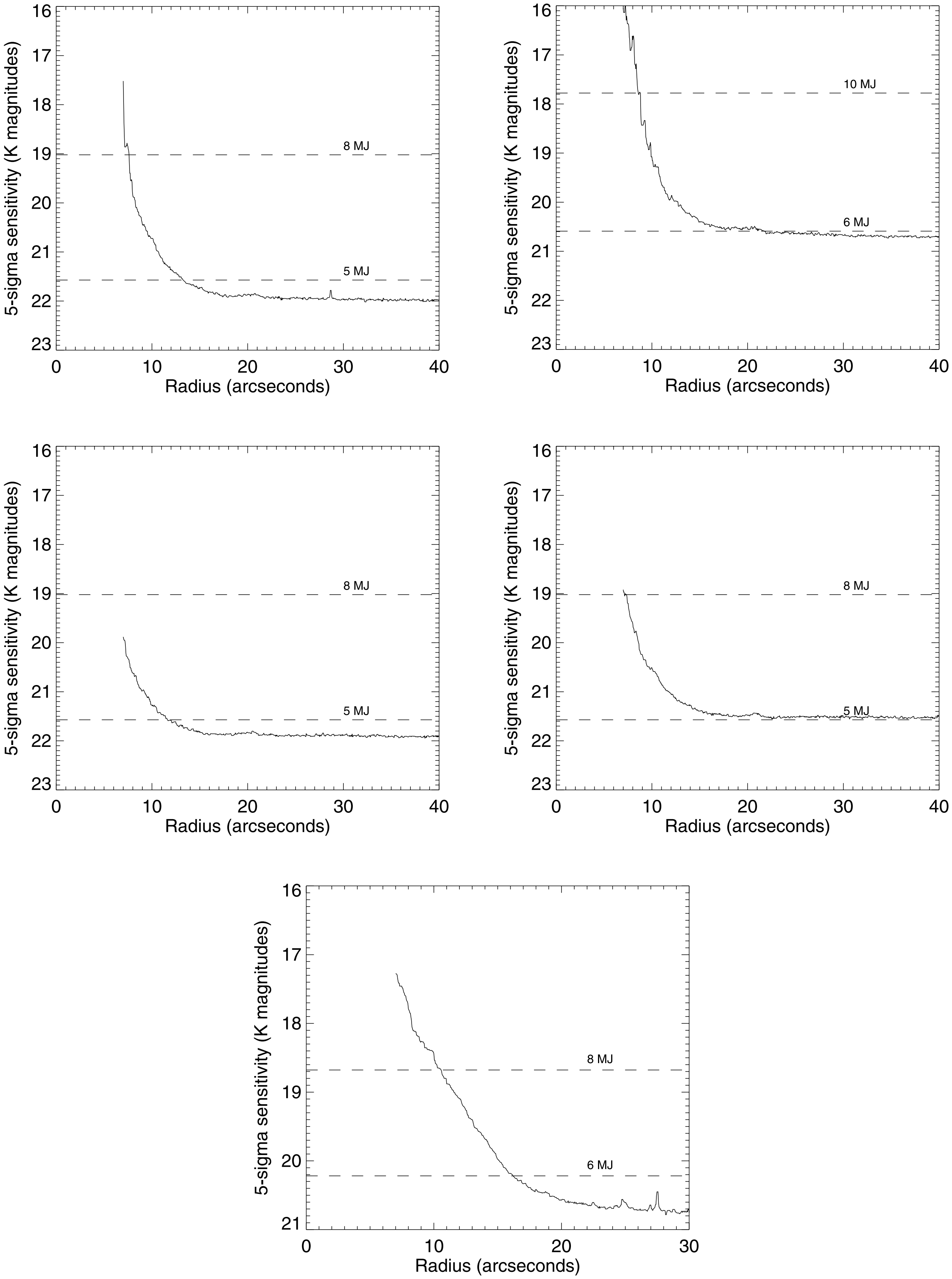

FIG. 4.—5 σ sensitivity of images of ϵ Eri east (*top left*), north (*top right*), south (*middle left*), west (*middle right*), and Vega (*bottom*). Horizontal lines show the magnitudes of extrasolar planets from the models of Burrows et al. (1997).

at the angular separations comparable to that of the dust rings. It is worth noting that our sensitivity was continuing to increase as $t^{1/2}$ during our observations—i.e., no systematic effects were limiting sensitivity at these large separations—and hence deeper imaging in the future could reach the 2–3 Jupiter mass level that some authors (Kuchner & Holman 2003) have predicted for the planet near Vega.

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