High-contrast imaging with Spitzer: deep observations of Vega, Fomalhaut, and $\epsilon$ Eridani

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ABSTRACT

Stars with debris disks are intriguing targets for direct-imaging exoplanet searches, owing both to previous detections of wide planets in debris disk systems, and to commonly existing morphological features in the disks themselves that may be indicative of a planetary influence. Here we present observations of three of the most nearby young stars, which are also known to host massive debris disks: Vega, Fomalhaut, and $\epsilon$ Eri. The Spitzer Space Telescope is used at a range of orientation angles for each star to supply a deep contrast through angular differential imaging combined with high-contrast algorithms. The observations provide the opportunity to probe substantially colder bound planets (120–330 K) than is possible with any other technique or instrument. For Vega, some apparently very red candidate point sources detected in the 4.5 $\mu$m image remain to be tested for common proper motion. The images are sensitive to $\sim 2 M_{\text{Jup}}$ companions at 150 AU in this system. The observations presented here represent the first search for planets around Vega using Spitzer. The upper 4.5 $\mu$m flux limit on Fomalhaut b could be further constrained relative to previous data. In the case of $\epsilon$ Eri, planets below both the effective temperature and the mass of Jupiter could be probed from 80 AU and outward, although no such planets were found. The data sensitively probe the regions around the edges of the debris rings in the systems where planets can be expected to reside. These observations validate previous results showing that more than an order of magnitude improvement in performance in the contrast-limited regime can be acquired with respect to conventional methods by applying sophisticated high-contrast techniques to space-based telescopes, thanks to the high degree of PSF stability provided in this environment.

Key words. planetary systems – techniques: image processing – infrared: planetary systems

1. Introduction

A large fraction of the extrasolar planets that have so far been directly imaged reside in systems with massive debris disks (e.g., Marois et al. 2008; Lagrange et al. 2010; Rameau et al. 2013). This may imply some correlation between at least wide massive planets and such disks. Furthermore, many debris disks show signs in both infrared excess (e.g., Hillenbrand et al. 2008; Trilling et al. 2008) and spatially resolved imaging (e.g., Schneider et al. 1999; Kalas et al. 2005) of having ring-like structures with inner gaps and cavities, sometimes with eccentric shapes. While alternative possibilities exist for explaining these structures (e.g., Lyra & Kuchner 2013), such rings may be shaped by planets orbiting near the ring edges (e.g., Quillen 2006). It is therefore interesting to study the regions close to the edges in particular detail (e.g., Apai et al. 2008; Janson et al. 2013a). While many planetary imaging surveys are performed at $JHK$-band ($\sim 1–2.5$ $\mu$m) wavelengths (e.g. Chauvin et al. 2010; Nielsen et al. 2013; Brandt et al. 2014), there is considerable interest in studying planets at longer wavelengths, in the $LM$-band range ($\sim 3–5$ $\mu$m). For ground-based telescopes, one of the reasons for this is the enhanced point spread function (PSF) stability (e.g., Kasper et al. 2007; Janson et al. 2008; Heinze et al. 2008), but a more general reason is that only warm planets of $\sim 400$ K effective temperatures and higher emit any significant flux at $JHK$-band. At lower temperatures, the flux in this region drops rapidly, while significant flux remains at longer wavelengths. Indeed, a wealth of results, including some of the planet detections mentioned above, have been achieved in the $3–5$ $\mu$m wavelength regime. However, a dominant limiting factor, in particular for ground-based telescopes, is the high level of thermal background noise that occurs even for cooled instruments.

The source $\epsilon$ Eri is a K2V-type star at a distance of 3.2 pc, Fomalhaut is an A4V star at 7.7 pc, and Vega is an A0V star at 7.7 pc (Perryman et al. 1997; van Leeuwen et al. 2007). They all have large debris disks with inner gaps, and they all have ages of a few to several hundred Myr, as discussed in subsequent sections. This makes them exceptional targets for planet imaging studies, and indeed, a large number of dedicated imaging studies of these targets have been performed as the field has developed (e.g., Macintosh et al. 2003; Metchev et al. 2003; Janson et al. 2007, and the many others mentioned in the discussion of individual objects below). Furthermore, they have all had candidate planetary companions inferred around them. Fomalhaut b is a visible-light point source observed with the Hubble Space Telescope (HST), as reported in Kalas et al. (2008). The point...
source corresponds to a real physical object bound to the system, but its exact nature remains unclear (e.g., Janson et al. 2012; Galicher et al. 2013; Kalas et al. 2013, and this paper).

Hatzes et al. (2000) reported ε Eri b as a radial velocity signature with a ~7 yr period. The semi amplitude suggested a mass in the jovian range. Later studies have supported this statement through astrometric measurements of the host star (Benedict et al. 2006; Reffert & Quirrenbach 2011). However, subsequent radial velocity studies with better precision have been unable to verify the existence of the planet (e.g., Anglada-Escudé & Butler 2012; Zecharia et al. 2013), implying a spurious detection or significantly different orbital parameters than those originally reported. All systems have had general predictions of planets from the disk morphology, and in the case of Vega, a rather specific prediction of the precise location of a planet has been made on the basis of what was interpreted as resonant features in the disk (Wilner et al. 2002; Deller & Maddison 2005). The underlying image, however, was based on interferometry with relatively limited coverage of the UV plane, and subsequent studies have not verified this morphology (e.g., Hughes et al. 2012).

In pioneering work by Marengo et al. (2006), it was shown that Spitzer could place stronger limits on wide separation planets in the ε Eri system than any other existing facility. The detection limits were further improved for this system in Marengo et al. (2009), where Fomalhaut was also studied to a similar degree of sensitivity. Subsequently, in Janson et al. (2012) a dedicated high-contrast observational and data reduction scheme was applied which further substantially enhanced the detection limit of Spitzer in the contrast-limited regime. This made it clear that the Spitzer Space Telescope could be efficiently used for high-contrast imaging at 4.5 μm, although the small aperture size of the telescope (0.85 m) limits the angular separation from the central star down to which the telescope can efficiently probe. The three stars described above are all very nearby, which places even modest physical separations at large angular separations, and they are thus ideal targets to study with Spitzer, allowing for much colder planets to be detected than are available with any other existing technique or telescope.

Here we report on a dedicated survey for acquiring deep observations at multiple orientation angles of the telescope for Vega, Fomalhaut, and ε Eri, and the results attained from applying angular differential imaging and high-contrast algorithms to the data. In Sect. 2, we describe the observing strategy and the basic data reduction, and in Sect. 3 we outline the PSF subtraction method used in the study. The individual results for the three targets are described in Sect. 4. We summarize the overall results and conclusions in Sect. 5.

### Table 1. Log of observing dates and angles.

| Target | AOR      | Date | PA (°) |
|--------|----------|------|--------|
| ε Eri  | 47936512 | 2013-03-19 | 58.1 |
| ε Eri  | 47936768 | 2013-03-31 | 64.8 |
| ε Eri  | 47937024 | 2013-04-08 | 69.0 |
| ε Eri  | 47937280 | 2013-04-22 | 75.5 |
| ε Eri  | 47937556 | 2013-10-22 | 106.0 |
| ε Eri  | 47937792 | 2013-10-29 | 102.8 |
| ε Eri  | 47938048 | 2013-11-08 | 98.2 |
| ε Eri  | 47938304 | 2013-11-27 | 88.4 |
| Fomalhaut | 47938560 | 2013-01-19 | 59.6 |
| Fomalhaut | 47938816 | 2013-01-23 | 61.1 |
| Fomalhaut | 47939072 | 2013-01-26 | 62.2 |
| Fomalhaut | 47939328 | 2013-02-10 | 67.4 |
| Fomalhaut | 47939584 | 2013-08-06 | –115.0 |
| Fomalhaut | 47939840 | 2013-08-10 | –113.5 |
| Fomalhaut | 47940096 | 2013-08-22 | –109.4 |
| Fomalhaut | 47940352 | 2013-08-28 | –107.1 |
| Vega  | 47934720 | 2013-06-11 | –92.2 |
| Vega  | 48354816 | 2013-06-17 | –96.9 |
| Vega  | 47934976 | 2013-07-04 | –111.8 |
| Vega  | 47935252 | 2013-08-21 | –156.7 |
| Vega  | 47935488 | 2013-08-09 | –175.6 |
| Vega  | 47935744 | 2013-10-16 | 143.8 |
| Vega  | 47936000 | 2013-11-27 | 104.7 |
| Vega  | 47936256 | 2013-12-05 | 97.8 |

2. Observations and data reduction

All observations in this work were acquired using the IRAC camera on the Spitzer Space Telescope. The three targets ε Eri (03:32:55.84, –09:27:29.71), Fomalhaut (22:57:39.05, –29:37:20.1), and Vega (18:36:56.34, +38:47:01.3) were observed with an identical observing scheme, building on the procedure developed for Fomalhaut as described in Janson et al. (2012). Each target was observed on eight different occasions across Spitzer cycle 9, which for regular programs ran from January through December of 2013. The eight occasions were spread out as much as possible within and across the observing windows available for each target during the cycle. This was done in order to optimize the observations for angular differential imaging (ADI) performance. ADI is a technique in which the target star is observed at several different rotation angles of the telescope, so that it can act effectively as a PSF reference for itself, as any off-axis sources will be located at different position angles in each data set. The wider the spread in rotation angles at which the telescope is observed, the smaller separations can be usefully probed with ADI. Since Spitzer is unable to actively roll, we take advantage of the fact that it exhibits a nominal roll across a year, and so a maximally spread out scheduling of the various observations facilitates an optimal ADI performance. Each of the eight visits for a given target consists of a series of 96 consecutive exposures, of which 48 are in the 3.6 μm and 48 in the 4.5 μm channel. A 12-point Roleaux dither pattern is used for oversampling purposes. Individual exposures have 10.4 s of effective integration time, leading to a total frame time of 12 s. A log of the dates and position angles for the 24 target visits (eight visits for each of three targets) is provided in Table 1.

For data reduction purposes, we used the post-BCD data from the Spitzer Heritage Archive, for which the fundamental reduction steps such as flat fielding and dark subtraction have already been performed. Although some bad pixel identification and removal has also been performed on these data, there were a few residual bad pixels present in the frames, hence we ran an additional bad pixel removal scheme in the same way as was described in Janson et al. (2012), by identifying outliers from the median of each quadruple set of frames corresponding to one particular dither position in an observing sequence. Next, the frames from all runs for a given target were registered to a common center, which cannot be done on the PSF core as it is always saturated in the images. Instead, this was done by cross-correlating each frame with a 180° rotated version of itself. For this purpose, only the six PSF spider arms were used, selecting 10 pixel wide strips from 20 to 70 pixels separation on each spider arm. The resulting centers were checked visually and also compared with an approximate center based on Gaussian centroiding on a strongly low-pass filtered version of

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1 All coordinates are in hh:mm:ss, dd:mm:ss and J2000.0 format.
each frame. In the vast majority of cases, the registering yielded a center that was accurate and consistent between the various checks, but in a few cases the result of the automatic centering was visibly off center; in these cases, we redid the automatic centering with a different cross-correlation window, typically from 10 to 30 pixel separation on the spider arms. Following this procedure, a satisfactory centering was found for the full set of images. Although the comparison strategy of Gaussian centering on a low-pass filtered version of the frame is considered less precise due to the broadening of the PSF in the process, the standard deviation in the di-

terence on a low-pass filtered version of the frame is considered of images. Although the comparison strategy of Gaussian cen-
tering with a di-

ference in the coordinates from the di-

erent cross-correlation window, typically different results,


e close to the star where we can substantially improve on pre-

vious work, we also limit the optimization to within 130 pixels from the star center for Fomalhaut and ε Eri, and within 150 pix-

els from the star center for Vega. In order to keep array sizes manageable, we make separate PCA subtractions for different regions: In the case of Fomalhaut and ε Eri, we use three re-
gions with the first between 20 and 50 pixels in radius, the second between 50 and 100 pixels, and the third between 100 and 130 pixels. For Vega, we use two regions where the first ex-


dents from 40 to 100 pixels and the second extends from 100 to 150 pixels. The boundaries of the full concatenated optimiza-
tion regions correspond to 19–125 AU for ε Eri, 46–300 AU for Fomalhaut, and 92–347 AU for Vega. Each PSF subtraction uses the first 100 PCA modes by default. The reduction results are not strongly dependent on the number of modes chosen.

After subtraction, all the individual images are de-rotated so that North points in the positive y-direction and East in the negative x-direction. A median combination was used to genera-
te one final frame per target. In order to get a broad general view of the field of view outside of the optimization re-
gions, we also produce ADI-subtracted full-field frames where only the mean PSF is used as a PSF reference (again after re-
quiring at least 1 FWHM of motion between target and refer-

ence frames), with no LOCI or PCA-based optimization. Since all of the full frame fields have several point sources in them, the 3.6 μm and 4.5 μm frames are carefully compared to check if any very red objects exist among them. In order to reproduce the total infrared flux of the point sources in question, any real phys-

ical companion would have to be more than an order of mag-
nitude fainter in the 3.6 μm band than the 4.5 μm band (e.g., Spiegel & Burrows 2012). With the exception of a few point sources around Vega that will be discussed in Sect. 4.3, all signif-

icant point sources could be recovered at both wavelengths and none were more than a factor of ~2 fainter in the 3.6 μm band than the 4.5 μm band, hence these point sources are all probable background stars. While there are no known contaminant point source objects that are as red as <400 K companions in these bands, we nonetheless consider it necessary for any candidate to be tested for common proper motion before anything can be said with confidence about its nature.

An actual companion in the data would inevitably suffer some partial flux loss during the PSF subtraction, so it is vital to robustly estimate the actual throughput of such a companion in order to be able to evaluate the real contrast performance of the algorithm. We use the procedure suggested as part of KLIP in Soummer et al. (2012) where an image of an artificial com-

panion is projected on the basis set that was constructed from the reference images. For Fomalhaut and ε Eri, the artificial companion is sequentially placed at every combination of eight different position angles (0°, 45°, 90°, etc.) and seven separations (five at 25–45 pixels in steps of 5 pixels, one at 75 pixels and one at 115 pixels). We then calculate the throughput (flux measured in a 1 FWHM diameter circular aperture centered on the com-

panion before versus after subtraction) for all cases and evaluate the mean and median of the azimuthal points for each radial step, in order to get composite throughput estimations as a function of separation. Since there is quite a lot of azimuthal structure in the images, with the six spider arms and other asymmetric PSF fea-
tures, the mean and the median can give quite different results, with the median predicting a higher throughput at most separa-
tions (e.g. 95.6% versus 85.1% at a 45 pixel separation), except at the smallest radii where the opposite is sometimes true (e.g. the mean predicting 48.2% and the median predicting 47.0% at a 25 pixel separation). In the course of this study we will use the

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2 http://irsa.ipac.caltech.edu/data/SPITZER/docs/irac/
mean estimator throughout. For Vega, the procedure is exactly the same as for the other two targets, except that the separations at which the throughput is evaluated are at 50–90 pixels in steps of 10 pixels, and at 125 pixels.

In order to evaluate the sensitivity in the final images, we calculate the standard deviation of pixels in concentric annuli around the star with widths of 1 pixel, from the inner to the outer edge of the optimization region. These are then related to the zero-point flux of Vega to acquire sensitivities in Vega magnitude (see Marengo et al. 2009). We use 5σ detection limits throughout this analysis. The throughput of a signal at each pixel separation is calculated through a linear interpolation between the points at which it is explicitly evaluated (as described above) for the innermost range (20–50 pixels for Fomalhaut and ε Eri, 40–100 pixels for Vega). For the 50–100 and 100–125 pixel ranges (100–150 pixels for Vega), the throughput at the center separation in the range is adopted. These throughputs are included in the sensitivity estimates. All curves presented in subsequent sections of this paper correspond to the 4.5 μm data, since this provides by far the best sensitivity to any planetary companions that may reside in the system. Mass and effective temperature sensitivities are estimated from the flux sensitivities using evolutionary COND-based models (Allard et al. 2001; Baraffe et al. 2003) and the age limits for the respective targets discussed in the following section. It can be noted that the classical discrepancy between so-called hot- and cold-start models (e.g., Marley et al. 2007; Spiegel & Burrows 2012) has no relevance for any companions that could be detected in this study, since they would be far too old and cold to retain any memory of their initial entropy. Aside from our choice of a 5σ significance criterion instead of a 3σ one, the only difference between how the sensitivity is evaluated here versus how it is evaluated in Marengo et al. (2009) is that we are evaluating the standard deviation in single-pixel annuli, whilst Marengo et al. (2009) evaluate it in annuli of 2 FWHM widths. These methods are equivalent for the purpose of determining a characteristic contrast at a given separation. The only difference is that a wider annulus gives a coarser spatial sampling on one hand, and less point-to-point scatter in the sensitivity curve on the other hand.

4. Results and discussion

In this section, we discuss separately the results acquired for the three targets observed in the study.

4.1. ε Eridani

No significant very red candidates were discovered in the final PCA-reduced image of ε Eridani (see Figs. 1 and 2), but the achieved sensitivity was excellent, allowing us to place strong upper limits on the flux (and thus temperature and mass) of any wide companions in the system. The sensitivity curve is plotted in Fig. 3. This sensitivity can be compared to the previous detection limits in the Marengo et al. (2009) study, by noting that the 3σ sensitivity is given as 13.60 mag at 10″ and 14.55 mag at 15″ there. Translating this into 5σ values results in 13.05 mag at 10″ and 14.00 mag at 15″. By comparison, the corresponding sensitivities acquired here are 15.89 mag and 16.73 mag, respectively. This is more than an order of magnitude increase in contrast, very similar to what we demonstrated in Janson et al. (2012) for Fomalhaut. Hence, this demonstrates once again that the use of multi-angle ADI and a large number of reference frames can significantly enhance the contrast performance in Spitzer data relative to standard two-angle differencing.

Adopting an age range for ε Eri is necessary for formulating the sensitivity in terms of detectable companion mass. In Janson et al. (2008), an examination of several different age diagnostics from the literature resulted in an age range of 200–800 Myr. However, the lower end of this range comes from a purely kinematic analysis (Fuhrmann 2004), which compared to more recent and in-depth studies related to young co-moving associations (e.g., Schlieder et al. 2012; Malo et al. 2013) must be considered as a rather loose constraint. Hence, we disregard it for the purpose of this study. In the meantime, Mamajek & Hillenbrand (2008) performed a study of activity and gyrochronology in nearby stars including ε Eri, deriving age estimates of 400 Myr and 800 Myr with two different methods. These estimates are in excellent agreement with the remaining range of ages considered in Janson et al. (2008), and so for this study, we simply adopt an age range of 400–800 Myr. Given this age range, we derive model-dependent mass detection limits as shown in Fig. 4.

In Janson et al. (2008), it was shown from a combination of imaging and radial velocity constraints that no planets more massive than 3 $M_{\text{jup}}$ could reside anywhere in the system, at least inside of the ∼500 AU field radius of Spitzer, even at the upper bound of the system age. Our new Spitzer limit further underlines this conclusion, and strengthens it with yet tighter constraints at wide separations. Even sub-Jovian planets can be discovered in some parts of the system – from ∼28 AU and outward for young system ages and from ∼48 AU and outward for old ages. As mentioned previously, it is of particular interest to study the regions close to the inner and outer edges of the debris ring. In the case of ε Eri, the ring extends from approximately 35 AU to 90 AU (Backman et al. 2009). Thus, including projection effects, ∼30–35 AU is the interesting range for the case of the inner edge. Here, we can exclude planets more massive than 0.8–0.9 $M_{\text{jup}}$ if the system age is 400 Myr, and planets more massive than 1.3–1.6 $M_{\text{jup}}$ if the age is 800 Myr. For the case of the outer edge, we can exclude planets more massive than 0.6 $M_{\text{jup}}$ at 78–90 AU if the age is 800 Myr.
All significant point sources have detectable flux in both channels, while planets in the system would only be detectable in the 4.5 μm channel. In the outer ranges of the image where PCA-based subtraction has not been applied, the imperfect background removal from a simple median subtraction leads to an asymmetric background distribution between the upper right and lower left sections of the image.

### Fig. 2.
Final reduced composite image of a wider field around ε Eri, at both 3.6 μm (left) and 4.5 μm (right). All significant point sources have detectable flux in both channels, while planets in the system would only be detectable in the 4.5 μm channel. In the outer ranges of the image where PCA-based subtraction has not been applied, the imperfect background removal from a simple median subtraction leads to an asymmetric background distribution between the upper right and lower left sections of the image.

### Fig. 3.
5σ sensitivity limits in terms of apparent magnitude in the 4.5 μm band, for the targets ε Eri (blue, solid line), Fomalhaut (green, dash-dotted line), and Vega (red, dashed line). Since Vega is brighter than the two other targets, it is less sensitive to very faint companions due to the bright PSF wings. Fomalhaut is slightly brighter than ε Eri, but since a larger amount of data is accessible for the case of Fomalhaut (see Sect. 4.2), the contrast performance is increased, and so for the inner parts of the separation range an approximately equal performance is attained for those two targets.

### Fig. 4.
5σ sensitivity limits in terms of detectable planet mass for ε Eri, based on COND models. The models only extend down to 0.5 M_Jup, thus the graph cuts off at that point. Aside from the Spitzer high-contrast data represented here with solid lines, the plot also shows, as dashed lines, the sensitivity from Janson et al. (2008) at smaller separations. The lower, blue points represent an age of 400 Myr, and the upper red lines an age of 800 Myr. The transition point between the different data sets is marked with a thin dashed line. Also plotted with vertical dashed lines are the inner and outer edges of the wide debris ring in the system. Gray lines are the minimum projected separations for a system inclination of ~30° (Saar & Osten 1997; Greaves et al. 1998). The full field stretches out to 400 AU with a roughly uniform sensitivity-limited performance, but has been cut off here to highlight the inner regions. When these imaging limits are combined with limits from radial velocity data (e.g., Hatzes et al. 2000; Zechmeister et al. 2013), it can be concluded that no planets more massive than 3 M_Jup can exist anywhere inside of ~500 AU in the system.
4.2. Fomalhaut

For Fomalhaut, the quality of the PCA-reduced data of the second epoch alone (see Fig. 6) is significantly worse than for the first epoch presented in Janson et al. (2012). The cause of this is unclear. A PCA re-reduction of the first epoch data confirms that this is an intrinsic feature of the data and not due to the reduction. The difference is large enough that co-adding the full two epochs offers no improvement in S/N versus using the first epoch by itself. Examining the individual frames after PCA reduction but before median collapse shows that indeed, the individual standard deviations of pixels in the optimization region are higher on average for the second epoch than the first epoch. However, there is a significant spread in the scatter among individual frames in both epochs, such that some second epoch frames still exhibit smaller scatter than some first epoch frames. As a consequence, we attempt to maximize the S/N of the combination of both data sets by selecting the optimal combination of frames for this purpose. We do this by sorting the combined set of PCA-reduced frames by their scatter, and calculating the S/N that would result from combining an incremental number of frames, starting from the smallest scatter and working upward. The calculation is based upon the assumption of the noise being independent between frames, such that it combines in a root-mean-square fashion. A resulting plot is shown in Fig. 7, which demonstrates that there is indeed an optimal number of frames to be combined, after which adding more frames with incrementally larger scatter will only decrease the final S/N. We thus produce a median-combined frame of the 203 frames selected in this manner. As expected, the final frame does constitute a modest improvement over the first epoch alone or the full combination of both epochs, so we use this frame for all future purposes in this paper.

The final images are shown in Figs. 6 and 8. There are no very red candidates in the images, although the closest candidate straight to the East in Fig. 6 has a strange appearance in the 3.6 μm channel, in that a dark streak appears to coincide with the point source. In Janson et al. (2012), we pointed out a possible point source to the South that was statistically insignificant but nonetheless worthy of some further attention. With the addition of new data, the point source disappears, confirming that it was most likely a spurious speckle. The azimuthally averaged detection limit is shown along with the other targets in Fig. 3. Since it is particularly interesting to evaluate the sensitivity at the location of Fomalhaut b (Kalas et al. 2008), and since the sensitivity varies a lot across the field as noted earlier, we calculate explicitly the sensitivity at that location, through the standard deviation in a 5-by-5 pixel box. We also evaluate the throughput at that particular location by imposing a false companion in the non-reduced data and transmitting it through the reduction procedure and comparing the flux before and after. Here, the throughput is 87.9%, which is intermediate between the median and mean throughputs at this separation. The resulting 5σ sensitivity at the location of Fomalhaut b is 17.3 mag, a 0.4 mag improvement on the original epoch. In Janson et al. (2012), we used the Spiegel & Burrows (2012) models to derive a mass limit of 1 M_jup from the previous detection limit at an age of 400 Myr. The difference in the IRAC 4.5 μm band at this age between a 0.5 M_jup and a 1 M_jup planet in the Spiegel & Burrows (2012) models is 0.8 mag, so an interpolation would imply a sub-Jovian mass in the range of 0.75 M_jup in this circumstance. The COND models predict a broadly consistent though slightly higher mass of 1.0 M_jup for an age of 400 Myr (and 1.2 M_jup for 500 Myr).

Since the full combination of two data sets spans a rather long time baseline, it is relevant to consider whether orbital motion could affect the detectability. If Fomalhaut b had moved enough between the two epochs, its signatures from each respective epoch would not co-add, but rather there would be two separate signatures in the final image. However, this effect can be easily estimated since it is known from HST observations how the object moves. Between the two latest reported epochs from Kalas et al. (2013), the object moves at a rate of 124 mas/yr. The difference between the mean observational epoch of our two data sets is 2.4 years, leading to a total estimated motion of approximately 300 mas. This is equal to one oversampled Spitzer pixel, and much smaller (by close to a factor 6) than the FWHM. Thus, the signatures will co-add efficiently and orbital motion of Fomalhaut b can be considered negligible in this context.

The average COND-based mass detection limit is shown in Fig. 9. Limits of 400 Myr and 500 Myr are used to bracket the age, which corresponds broadly to the age estimate of 440 ± 40 Myr for the Fomalhaut system provided in the detailed study by Mamajek (2012). The temperature detection limit is shown in Fig. 5. As can be seen, planets in the range of 1.5–3 M_jup and 250–330 K are detectable on average in the range of 50–100 AU. Although alternative scenarios have been proposed (e.g., Lyra & Kuchner 2013), the morphology of the Fomalhaut disk has been proposed to possibly imply the presence of massive planets (e.g., Quillen 2006). Thus, our study provides the most robust available upper limits for the masses of any such planets in wide (>50 AU) orbits. See Kenworthy et al. (2013) and Currie et al. (2013) for summaries of constraints from a range of observations.

As we showed already in Janson et al. (2012), the upper limit on 4.5 μm flux at the location of Fomalhaut b firmly excludes the possibility that any noticeable fraction of the visible-light flux observed in the Hubble images constitutes thermal radiation from a giant planetary surface. Rather, the flux represents reflected emission from the star against dust in some configuration.
As for the case of $\epsilon$ Eri, all point sources in the image have detectable signatures in both channels, consistent with background stars. The point source marked with an arrow has a strange morphology at 3.6 $\mu$m, possibly due to it coinciding with a residual spider feature. In the outer ranges of the image where PCA-based subtraction has not been applied, the imperfect background removal from a simple median subtraction leads to an asymmetric background distribution between the upper right and lower left sections of the image.

**Fig. 7.** S/N gain factor as a function of cumulative addition of individually PSF-subtracted frames sorted from least to greatest individual scatter. As the frames become progressively worse, they add less and less to the final S/N, and eventually decrease the quality rather than increasing it. It follows that the best 203 frames provide the ideal ensemble to combine for optimizing the total S/N.

4.3. Vega

Since Vega is a bit brighter than the other two targets and the observing parameters were identical, it saturates out to a farther angular separation of about 40 pixels. We thus perform the PCA-based reduction in an area of 40–150 pixel radius from the star, as described in Sect. 3. The innermost region of the system is shown in Fig. 10 and a wider field is shown in Fig. 11. There are no unambiguously interesting candidates in the final reduced frame, but there are a few cases that deserve special attention. These are marked out in the latter figure.

Feature “1” is not statistically significant (only 2.7 $\sigma$) in the KLIP reduction, but it appears at 6.2 $\sigma$ in the PynPoint reduction. The feature appears to reside in an angular range that is particularly affected by spider features, and so we consider it a likely spurious feature, since it is not significant in the quantitatively better KLIP reduction. For feature “2”, it is unclear whether or not the 4.5 $\mu$m feature (which is significant at 5.2 $\sigma$) has a 3.6 $\mu$m counterpart. Our preliminary assessment is that it is a slightly red background object, but further observations would be useful to verify this. Feature “3” is another case of a 4.5 $\mu$m feature (5.6 $\sigma$ significance) with no 3.6 $\mu$m counterpart, and is perhaps the most promising of the candidates. However, while the feature is point-like in the KLIP reduction, it appears more extended in the radial direction in the PynPoint reduction, again raising the possibility that it might be a residual spider feature. Follow-up observations would be useful for further testing all of these cases. If interpreted as real, physically bound companions, their projected separations correspond to $\sim 265–335$ AU, and their fluxes correspond to masses of $\sim 2–3 M_{\text{jup}}$ at ages of 400–800 Myr.

The sensitivity curve for Vega is included in Fig. 3. The higher limits around Vega than the other targets stem from the fact that an approximately equal contrast is achieved as for the other targets, but around a brighter target star. The age of Vega
Fig. 8. Final reduced 4.5 μm images of the innermost region in the Fomalhaut system. **Left:** the actual image, with no candidates present. **Right:** an image in which an artificial companion has been inserted at the expected location of Fomalhaut b prior to the high-contrast reduction, illustrating that companions are well preserved in the procedure, with little flux loss. The artificial companion in this example corresponds to a planet of mass 1.6–1.8 M\(_{\text{jup}}\) at 400–500 Myr using COND models.

Fig. 9. 5σ sensitivity limits in terms of detectable planet mass for Fomalhaut, based on COND models. The lower blue (400 Myr age) and upper red (500 Myr) curves are the azimuthally averaged sensitivities. These sensitivities vary significantly over the field of view, and in the expected location of Fomalhaut b, they are better than average. They are illustrated by points at a bit over 100 AU in the figure.

is typically estimated through isochronal techniques in the literature, and recent estimates have varied fairly significantly in the literature (Song et al. 2001; Yoon et al. 2010; Monnier et al. 2012). Here we adopt an age range of 400–800 Myr to encompass this uncertainty. This leads to model-based mass detection limits as shown in Fig. 12, with a sensitivity to 3–4 M\(_{\text{jup}}\) planets at ~100 AU. The disk boundaries plotted in Fig. 12 are based on the estimated half-maximum points of the 1 mm optical depth in Marsh et al. (2006). As argued in e.g. Boley et al. (2012), the relatively large grains probed at such wavelengths are probably more closely representative of the parent planetesimal body distribution than dust probed at shorter wavelengths (e.g., Sibthorpe et al. 2010), which imply a somewhat different dust distribution.

When combining the *Spitzer* data to literature M-band limits (Heinze et al. 2008) using the same ages and the same evolutionary and atmospheric models, the mass limits close to the disk boundaries are 5–7 M\(_{\text{jup}}\) at the inner edge at ~50 AU, and ~2 M\(_{\text{jup}}\) at the outer edge near 145 AU. The detection limit in terms of effective temperature is included in Fig. 5. While not quite as sensitive in this regard as the Fomalhaut and \(\epsilon\) Eri limits, the Vega observation still allows for detection of objects with substantially lower temperatures than can be acquired at shorter wavelengths with currently existing instrumentation.
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Fig. 11. Final reduced composite image of a wider field around Vega, at both 3.6 μm (left) and 4.5 μm (right). There are some 4.5 μm point sources for which it is not clear if a 3.6 μm counterpart is present; see discussions in the text.

Fig. 12. 5σ sensitivity limits in terms of detectable planet mass for Vega, based on COND models. Aside from the Spitzer data analyzed here and plotted with solid lines, the figure also includes a limit from the MMT in dashed lines probing smaller separations in the system, by Heinze et al. (2008). Also shown with vertical dashed lines are the approximate inner and outer edges of the wide debris ring in the system. The lower blue lines correspond to a system age of 400 Myr, and the upper red lines to an age of 800 Myr.

5. Summary and conclusions

In this study, three stars that are both nearby, young, and have large debris disks with inner gaps were studied with Spitzer using high-contrast methods, in order to yield unprecedented sensitivity to cold, low-mass companions at wide separations. One of these targets was Fomalhaut, which had already been studied with the same technique in Janson et al. (2012) and which motivated this study. Although our new Fomalhaut data set was of worse quality on average than the previous epoch of data, a combination of the two data sets with selection of the best frames yielded improved sensitivity limits. In terms of mass sensitivity, the limits did not change much, as the improved flux sensitivity was counteracted by the fact that the system is now thought to be a bit older than previously believed (Mamajek 2012). Thermal radiation from Jupiter-mass or more massive planets can be excluded at the expected location of Fomalhaut b. Another observed target was Vega, for which we were sensitive to planets more massive than ~2 Mjup outside of the outer disk edge at 145 AU. A few candidates detected in the 4.5 μm image would greatly benefit from follow-up observations in the future aiming for a similar contrast performance, in order to better establish their nature. Particularly tight constraints on planetary properties could be set in the ϵ Eri system, due to its proximity. Prior to the observations presented here, it was possible to exclude that any planets more massive than 3 Mjup exist anywhere in the system inside of ~500 AU (Janson et al. 2008), based on a combination of radial velocity and imaging data. With these new Spitzer data, it was possible to place even stronger constraints at wide separations: For instance, planets more massive than 1.5 Mjup could be excluded at the inner edge of the ϵ Eri debris ring at 30–35 AU, and substantially sub-jovian mass planets could be excluded beyond the outer edge at 78–90 AU. Generally, planets with both the same mass (and thus equal surface gravity, for an equal radius) and same effective temperature as Jupiter could be excluded at wide separations, which is a thoroughly unique feature for this target.

These Spitzer observations probe a new parameter range of cold and wide planets, which are unattainable with any other existing telescope or instrument. In this way, it paves the way for the James Webb Space Telescope, which will offer observations in the same wavelength range in space but with a 6 m aperture instead of the 0.85 m aperture of Spitzer, greatly improving the sensitivity and spatial resolution. More generally, the results attained in Janson et al. (2012) and here, as well as the similar results from HST data (e.g., Lafrenière et al. 2009; Soummer et al. 2014), demonstrate the great benefit of applying high-contrast techniques and algorithms to space-based telescopes, with their high degree of PSF stability, which enables sophisticated PSF reference optimization. This has broad utility for high-contrast imaging, potentially including more advanced coronagraphy/occulter-based missions for imaging Earth-like planets in the habitable zones of nearby stars at some point in the future.

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