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An Enigmatic Pointlike Feature within the HD 169142 Transitional Disk

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ABSTRACT

We report the detection of a faint pointlike feature possibly related to ongoing planet-formation in the disk of the transition disk star HD 169142. The pointlike feature has a Δmag(L)$\sim$6.4, at a separation of $\sim$0.11$''$ and PA$\sim$0°. Given its lack of an H or K$_S$ counterpart despite its relative brightness, this candidate cannot be explained by purely photospheric emission and must be a disk feature heated by an as yet unknown source. Its extremely red colors make it highly unlikely to be a background object, but future multi-wavelength followup is necessary for confirmation and characterization of this feature. [1] [2]

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[1]Based on observations made with ESO Telescopes at the La Silla Paranal Observatory under programme ID 091.C-0572.

[2]This letter includes data gathered with the 6.5 Magellan Telescopes located at Las Campanas Observatory (LCO),

Subject headings:

1. Introduction

Transition disks trace a key step in the formation of planetary systems, intermediate between gas-rich protoplanetary disks and debris disks, where primordial gas is cleared away, leaving only remnant dust. These disks are observationally identified by weak mid-IR emission (at $\sim$15 μm) relative to the Taurus median spectral energy distribution (Najita et al. 2007, i.e. the median SED of primordial disks in the young (<2 Myr) Taurus star-forming region). While numerous physical processes may be responsible for the depletion of gas and dust in transition disks, cleared gaps in particular may be an indicator of a planet or brown dwarf companion in the midst of formation. Thus, these disk systems have been key targets for direct imaging searches for planets.

Transition disks tend to be found in young star-forming regions >100 pc from Earth. Only recently have imaging techniques been available to probe the inner portions of these disks, where planets are likely to form. In the last few years, there have been a number of notable discoveries of companions in transition disks with cleared gaps. Via the interferometric sparse-aperture masking (henceforth SAM) technique (Lacour et al. 2011), Kraus & Ireland (2012) found LkCa 15b, a candidate protoplanet embedded within the disk of a $\sim$2 Myr solar analog. Biller et al. (2012) detected a 0.1-0.4 $M_\odot$ companion in the disk around the Herbig Ae/Be star HD 142527. This binary companion was recently confirmed and shown to be accreting via direct imaging (Close et al. 2014). HD 142527 has a particularly wide gap in its disk (> 10-120 AU, Fukugawa et al. 2006, Rameau et al. 2012, Casassus et al. 2012), which may be explained by a stellar companion on an eccentric orbit. Finally, Quanz et al. (2013a) reported an as yet unconfirmed candidate protoplanet detection in the disk of the Herbig Ae/Be star HD 100546.

The Herbig Ae/Be star HD 169142 possesses a nearly face-on transition disk, and has been studied in detail both spectroscopically (Meeus et al. 2001, van Boekel et al. 2005), and through imaging (Habart et al. 2006, Kuhn et al. 2001, Hales et al. 2006, Grady et al. 2007, Fukugawa et al. 2010, Honda et al. 2012, Mariñas et al. 2011). Recently, Quanz et al. (2013b) detected a well-resolved annular gap from 40 - 70 AU via polarized light imaging. Thus, like LkCa 15, HD 142527, and HD 100546, it is an excellent candidate to possess a planetary mass or brown dwarf companion in the midst of formation.

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2. Stellar Parameters

Adopted stellar parameters are presented in Table 1. In general, we adopt the stellar parameters from Table 1 of Quanz et al. 2013b. An accurate age estimate is particularly important for estimating candidate companion properties; HD 169142 has been assigned a fairly wide range of ages. Guimarães et al. 2006 assign a comparatively young age of 1-5 Myr based in HD 169142's HR diagram position, while Blondel & Djie 2006 claim a similar mass and age as β Pic for HD 169142. Grady et al. 2007 find a comoving companion 9.3" separated from HD 169142. This object is a 130 mas separation weak-line T Tauri binary, thus they assign an age of 6^{+6}_{-3} Myr for the entire system. For our analysis here, we thus adopt an age range of 3-12 Myr. Sylvester et al. 1996 derive a photometric distance of 145 pc to HD 169142, based on an A5 spectral type; Blondell & Djie 2006 update this to 151 pc based on a spectral type of A7V. As derived spectral type will strongly affect the photometric distance, we adopt a distance range of 145$\pm$10 pc here to account for any uncertainty in spectral typing.

3. Observations and Data Reduction

3.1. July 2013 VLT NACO Vortex Observations

First epoch observations were conducted using the novel annular groove phase mask (henceforth AGPM) vector vortex coronagraph (Mawet et al. 2013) with the NACO camera at the VLT (Lenzen et al. 2003; Rousset et al. 2003). The AGPM coronagraph uses an annular groove phase mask to redirect on-axis starlight out of the pupil (Mawet et al. 2005). In this manner, the AGPM coronagraph enables L' band contrasts of Δmag>7.5 mag at inner working angles down to 0.09$''$ (Mawet et al. 2013). HD 169142 was observed in L' from 02:47 UT to 04:54 UT on 14 July 2013, covering nearly an hour both before and after transit. The derotator was turned off to enable azimuthal differential imaging (ADI) techniques. Seeing varied from 1-2$''$ over the observation. We used a base exposure time of 0.25 s with 120 coadds and obtained a total of 1 hour 15 minutes on-sky exposure time. Sky frames were interspersed after every 20 frames and 0.05 s unsaturated exposures were taken at the beginning of the sequence. Care was taken to keep the primary star centered under the AGPM. Observation details are presented in Table 2.

Data were flat-fielded and bad-pixel corrected using dome flats and darks taken as part of ESO standard calibrations. Numerous dust spots are apparent on the AGPM, thus, slight misalignments between science and sky frames can produce significant cosmetic errors. Thus, we carefully selected the sky frame which minimized cosmetic errors for each science frame. Eleven science frames (out of 126 total science frames) which showed significant cosmetic errors even after sky subtraction were discarded. Each frame was centroided on the raw data using the idl routine mpfit2dpeak.

After basic data reduction and centroiding on the center of the coronagraphic mask using the IDL mpfit2dpeak routine, we analyze the data using 3 independent principal component analysis

(PCA) pipelines (following the algorithms of Soummer et al. 2012, Amara & Quanz 2012). All three pipelines yielded similar results – we report here the results using the publically available pipeline of Dimitri Mawet (http://www.sc.eso.org/∼dmawet/DimitriMawet/IDL_PCA_pipeline.html).

3.2. April 2014 Magellan AO Observations

Followup observations were conducted using the 585 actuator 1000 Hz adaptive secondary AO System (MagAO) at the 6.5m Magellan Clay Telescope (Close et al. 2013). With 378 corrected modes, the MagAO system is one of the highest sampled AO systems on a large telescope (>5 m) and has demonstrated high spatial resolutions (20-30 mas) in the visible (as short as λ =0.6μm, Close et al. 2013). MagAO feeds both a visible (VisAO, 0.5-1 μm) and infrared camera (Clio2, 1-5 μm) simultaneously.

We obtained a total of 5 datasets for HD 169142 with MagAO from 8-15 April 2014. Observing details are presented in Table 2. Four of these datasets were obtained with the Clio2 Narrow camera including two H band observations, one K_S band observation, and one 3.9 μm 5% filter observation. We also obtained a deep z' dataset using the VisAO camera. The derotator was turned off to enable angular differential imaging (ADI) techniques. All MagAO data was reduced in the standard manner (flat-field correction, sky-subtraction, bad-pixel correction). The H, K_S, and z' datasets remained unsaturated in the core, thus we align our images using the unsaturated core. We then process our data using the independent PCA-based pipelines of CoIs Rodigas and Males (see e.g. Rodigas et al. 2014 and Males et al. 2014). Both pipelines yielded similar results.

At 3.9 μm, we acquired data for HD 169142 as well as for a PSF star of similar magnitude. We achieved very high Strehl ratios for both stars in dry, photometric conditions. Seeing remained around 0.4-0.6″ for the entire night. After image registration, we built a PSF from the nearby star images and subtracted the PSF from each of our MagAO/Clio2 images of HD 169142, then rotated to place North up/East left. Our best subtraction is for a PSF scaling of 115%, which removes the Airy rings quite well. Dark pixels in the core are due to saturation/non-linearity.

4. Results

In July 2013, we detected a faint, pointlike feature in our L' vortex dataset at ∼0° PA, with a separation of ∼0.11". This pointlike feature was independently imaged in June 2013 by Reggiani et al. 2014. Multiband followup observations were conducted using Magellan AO in April 2014. Images from all epochs are presented in Figs. 1 and 2. Astrometry and photometry are presented in Table 1. The correct rotation to place north up and east left was verified at each epoch. For the July 2013 vortex data, a dataset on HD 142527 was acquired on the same run. The bright HD 142527 disk (see e.g. Fukagawa et al. 2006, Rameau et al. 2012) is correctly derotated by the pipeline. For the April 2014 MagAO data, the correct derotation has been validated using images of the Trapezium cluster.

4.1. July 2013 VLT NACO Vortex Observations

L' photometry and astrometry was derived for the pointlike feature by inserting scaled PSF images into the raw data and selecting the fluxes and positions that best match the actual feature. Best astrometry and photometry is presented in Table 1. Assuming a point source, our best subtraction yielded Δmag=6.4$\pm$0.2 for this feature, at a separation of 0.11$\pm$0.03$''$ and PA of 0$\pm$14°. Given that the inner working angle of the vortex coronagraph is 0.09$''$ (Mawet et al. 2013), this pointlike feature is marginally resolved at best.

To estimate the S/N level of our detection, we calculated the mean and standard deviation in a circular aperture with diameter of λ/D centered on the pointlike feature and in the 6 additional resolution elements available at this separation and then calculated S/N from equation 9 of Mawet et al. (2014) (appropriate for speckle-dominated regions):

$$S/N = \frac{\bar{x_1} - \bar{x_2}}{s_2\sqrt{1 + \frac{1}{n_2}}} \tag{1}$$

where $\bar{x_1}$ is the mean within the aperture containing the feature, $\bar{x_2}$ is the mean of the remaining 6 resolution elements, s_2 is the standard deviation of the remaining 6 resolution elements, and n_2 is the number of resolution elements not containing the feature. We find S/N$\sim$6 for the detected feature, thus this detection is unlikely to be a false positive – a result which is further bolstered by the independent detection of the same feature by Reggiani et al. 2014.

Initially assuming purely photospheric emission, we estimate mass using Monte Carlo methods to account for the range of possible ages and uncertainties in photometry for this system. An ensemble of 10^6 possible ages are drawn from a uniform distribution running from 3-12 Myr. An ensemble of 10^6 absolute magnitudes are simulated, assuming Gaussian errors on photometry and distance (0.3 mag error in Δmag, 10 pc error in distance). We then interpolate with age and single band absolute magnitude to find the best mass for the companion from the DUSTY and COND models of Chabrier et al. (2000) and Baraffe et al. (2002). Mass range histograms are presented in Fig. 2. Adopting a 3-12 Myr age range at a distance of 145 pc and the DUSTY models, this candidate would correspond to a relatively high mass 60-80 M_{Jup} brown dwarf.

4.2. April 2014 Magellan AO Observations

No counterpart to the L' detection was found in the April 2014 MagAO followup. Our non-coronagraphic 3.9 μm followup imaging was too shallow to retrieve the pointlike feature (Δmag=5.6 at 0.11"). However, a 60-80 M_{Jup} object at these ages should have been quite bright in the near-IR

(H band absolute magnitude <7) and have been easily detected given our H and K_s sensitivity. Indeed, our sensitivity is sufficient to detect a ∼7-15 M_{Jup} object at this separation and age range. Such a high-mass companion should open up a very wide gap in the disk, inconsistent with the ring at similar radii observed polarimetrically by Quanz et al. 2013b. The lack of a near-IR counterpart to the L' detection signifies that we are not observing the photosphere of a substellar object here but may be a potential disk feature its extremely red colors indicate that it is extraordinarily unlikely to be a background.

We performed radiative transfer calculations to investigate whether or not a passively heated disk 'feature' can reproduce the observed point-like source. We used the best fit disk model parameters from Maaskant et al. 2013 to describe an axisymmetric disk. Then to simulate a clump we increased the pressure scale height in the disk. The scale height was increased as a 2D Gaussian centered on the observed point source with an FWHM of 7 AU and a peak perturbation of 30%. We used 0.1 μm size astronomical silicates for the dust opacity to get an upper limit on the scattered light perturbations. Larger grains would scatter preferentially forward, perpendicular to the line of sight, which would decrease the contrast between the clump and the central star. Then we measured the contrast on the calculated L' images. We find that a "dust clump" at the position of our candidate would have a contrast of ∼17 mag (1×10^{-7}) between the star and the clump, much fainter than the detected candidate.

This result is not surprising, given the distance of the pointlike feature from the star. Assuming we observe only thermal dust emission from an irradiated clump, if the clump peaks at L', it would have T∼850 K. Thus, adopting this as the maximum temperature of a potential dust clump, an irradiated clump with this temperature would be at a distance of the order of 0.6 AU (considering temperature and radius of the primary from Quanz et al. 2013b), inconsistent with the >10 AU separation of this detection. Tentatively, we consider this candidate to be a disk feature heated by an as yet unknown mechanism.

We also marginally detected a candidate companion in H and Ks with a separation of ∼0.18" and a PA of ∼33°, but at low significance (S/N=3-5, using the same procedure as for the pointlike L' feature). These data were taken at two different nods, with very different looking PSFs in the two nods, limiting the precision of our photometry to ±0.5 mag. Thus, while this point source was detected in two different bands on 3 nights (with S/N∼5 in the first dataset, but only S/N∼3 in the additional datasets), it requires confirmation at an additional epoch, with a more stable PSF, to verify common proper motion and rule out imaging and reduction artifacts. If real and purely photospheric, this candidate would be a 8-15 M_{Jup} planet / substellar object (DUSTY and COND models). No corresponding L' counterpart was found in the July 2013 L' vortex dataset. If purely photospheric, the L' counterpart to this object is expected to have an absolute magnitude >8.5 mag (DUSTY or COND models), corresponding to an apparent magnitude of >14.3 mag. This is considerably below our achieved contrast for this dataset at this separation (limiting magnitude of ∼12.7, from insertion and retrieval of PSF images into the raw data). We also do not see a counterpart to this point source in our deep MagAO/VisAO z' dataset, down to a contrast of 10^{-4}.

If real, the very red colors of this object are inconsistent with background stars with spectral types earlier than mid to late M.

5. Discussion

The known geometry of this disk limits the potential masses of companions associated with imaged asymmetries. Quanz et al. 2013b image an inner dust ring peaking at 25 AU and an annular gap from 40-70 AU. The L' detection lies within the 25 AU dust ring and may be connected to ongoing companion formation in the disk. If associated with a massive object, it may have had some role in clearing out the region inside this ring. Our tentative H/K detection does not lie within the 40-70 AU gap but is coincident with the 25 AU dust ring. This suggests that any substellar/planetary counterpart to this tentative detection cannot be very massive, as a massive object ($\gtrsim$0.55 M_{Jup} should completely clear away dust from its immediate environment (Kley & Nelson, 2012). If massive objects are associated with these detections, they would be some of the closest companions imaged to date. Among confirmed directly imaged exoplanets, only β Pic b, HR 8799d, and HR 8799e have comparably small projected separations (Lagrange et al. 2010, Marois et al. 2008, 2010).

Some disk asymmetries detected via Sparse Aperture Masking (SAM) have been described due to forward scattering off an inclined disk (e.g. Cieza et al. 2013, Olofsson et al. 2013). However, HD 169142 is nearly face on (Quanz et al. 2013b), so forward scattering cannot have produced any observable structure in this case.

Our L' detection is also not well-described by dust features heated only by the central star; it is simply too far from the star to be heated enough to produce the observed emission. However, bright disk-related features have been observed in other transition disks. For instance, Kraus et al. 2013 detect bright asymmetries via sparse aperture masking in H, K', and L' band within the 15-40 AU inner gap in the pre-transitional disk V1247 Orionis. These asymmetries are not well-fit by a companion model; these authors attribute these features to spiral features or accretion streams due to the interaction of the dust disk with the substellar bodies inside the gap responsible for its clearing. Kraus & Ireland 2012 detect a protoplanet candidate (also via sparse aperture masking) around LkCa 15. While their detection is well fit by a single point source at K, the L detection appears extended and not entirely coincident with the K detection. They interpret the K detection as the protoplanet itself and the L detection as circumplanetary material potentially shocked and heated by jets from the protoplanet.

In the case of HD 169142, the possible energy source for the observed L' disk feature remains unknown. As previously noted, the lack of a H/K counterpart rules out photospheric emission and the L' detection is too strong to be described by passive heating from the star. If due to jets or accretion onto a forming planetary companion, we would expect a Hα counterpart to the L' detection (Close et al. 2014). However, Follette et al. in prep have observed HD 169142 with

MagAO in Hα and do not detect an Hα counterpart to the L' disk feature.

The L' detection may be related to emission line regions inside the HD 169142 disk. Habart et al. 2006 found strong 3.3 μm PAH emission (from a C-H stretching feature of neutral PAHs) in the HD 169142 disk out to 0.3" (using high-resolution AO-supported NACO long-slit spectroscopy and along a slit oriented north to south, i.e. intersecting our detection). Maaskant et al. 2014 also find strong PAH emission (however, primarily in ionized features) in the HD 169142 disk, likely stemming from the inner disk gap. A weak blue leak (on order 1%) in the NACO L filter might allow us sensitivity to PAH features in the disk. If our L' feature is indeed due to PAH emission, future 3.3 μm follow-up observations should easily retrieve this feature.

6. Conclusions

We report the detection of a faint pointlike structure in the HD 169142 transition disk, also independently detected by Reggiani et al. 2014. This structure has Δmag(L)$\sim$6.4, at a separation of $\sim$0.11$''$ and PA of $\sim$0°. Given its lack of an H or K_S counterpart despite its relative brightness, this object cannot be due to the photosphere of a substellar or planetary mass companion and must instead be a disk feature. However, the observed L' detection is too strong to be described by passive heating from the star and ongoing accretion is ruled out by the MagAO Hα non-detection of Follette et al. in prep. While the location of the L' pointlike feature right within the disk gap strongly suggests it may be connected to ongoing planet-formation (i.e. whatever process cleared out the gap), the energy source fueling this feature without producing a corresponding near-IR counterpart still remains mysterious. Hopefully, future multi-wavelength followup observations will elucidate the source of this feature – and perhaps in the process refine our understanding of ongoing planet-formation in this disk.

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Table 1. Properties of the HD 169142 System

	Primary	Disk Feature
Distance	145±10[a]	
Age	3-12 Myr[b]	
Proper Motion (μ_α, μ_δ)	(-2.1±1.5, −40.2±1.5) mas/yr[c]	
Separation: 14 July 2013 UT	···	0.11±0.03″ (∼16 AU)
Position Angle: 14 July 2013 UT	···	0±14°
$\Delta L'$	···	6.4±0.3
H (mag)	6.91[d]	···
Ks (mag)	6.41[d]	···
L' (mag)	5.64 [e]	12.0±0.3
$M_{L'}$ (mag)	-0.2	6.2±0.3
Spectral type	A7V[f]	···
Estimated Mass	1.65 $M_\odot$ [f]	···

[a]Sylvester et al. (1996), but errors derived here.

[b]Grady et al. (2007)

[c]Høg et al. (2000)

[d]From 2MASS

[e]Malfait et al. (1998)

[f]Blondel & Djie (2006)

Table 2. Observation log

Telescope/Instrument	UT Date	Band	Exposure Time	Field Rotation
VLT NACO Vortex	14 July 2013	L’	75 min	135.2
MagAO CLIO-2 Narrow	9 April 2014	H	46 min	178.5
MagAO CLIO-2 Narrow	10 April 2014	H	30.4 min	172.9
MagAO CLIO-2 Narrow	12 April 2014	K_S	70 min	180.1
MagAO CLIO-2 Narrow	15 April 2014	3.9μm	60 min	164.1
MagAO VisAO Narrow	15 April 2014	z_p	82.4	176.8

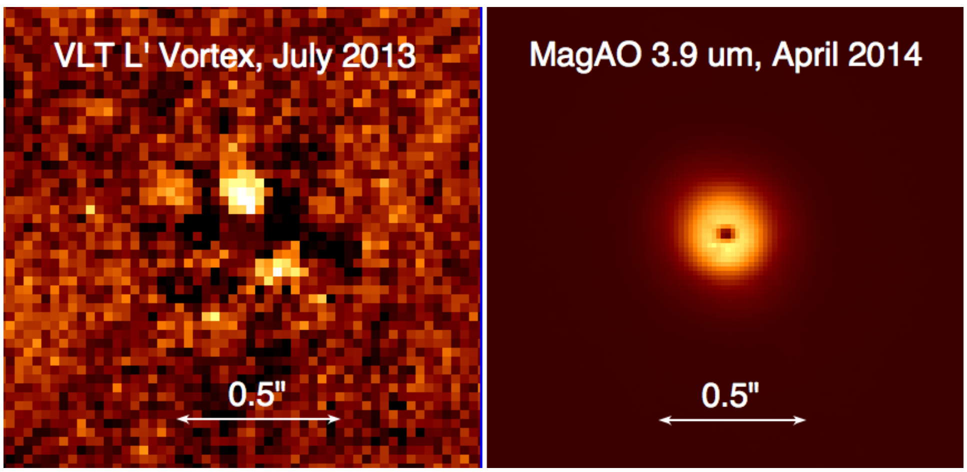

Fig. 1.— Left: L' July 2013 NACO Vortex image. We find a pointlike feature in the disk with Δmag=6.4±0.2, at a separation of 0.11±0.03$''$ and PA of 0±14°. Right: 3.9 μm April 2014 PSF-subtracted MagAO CLIO-2 image. Dark pixels in the core are due to saturation/non-linearity. The April 2014 MagAO image reached shallower contrasts than the original vortex image, hence the faint point-like feature is not retrieved. Our noncoronagraphic dataset was too shallow to retrieve the candidate (Δmag=5.6 at 0.11").

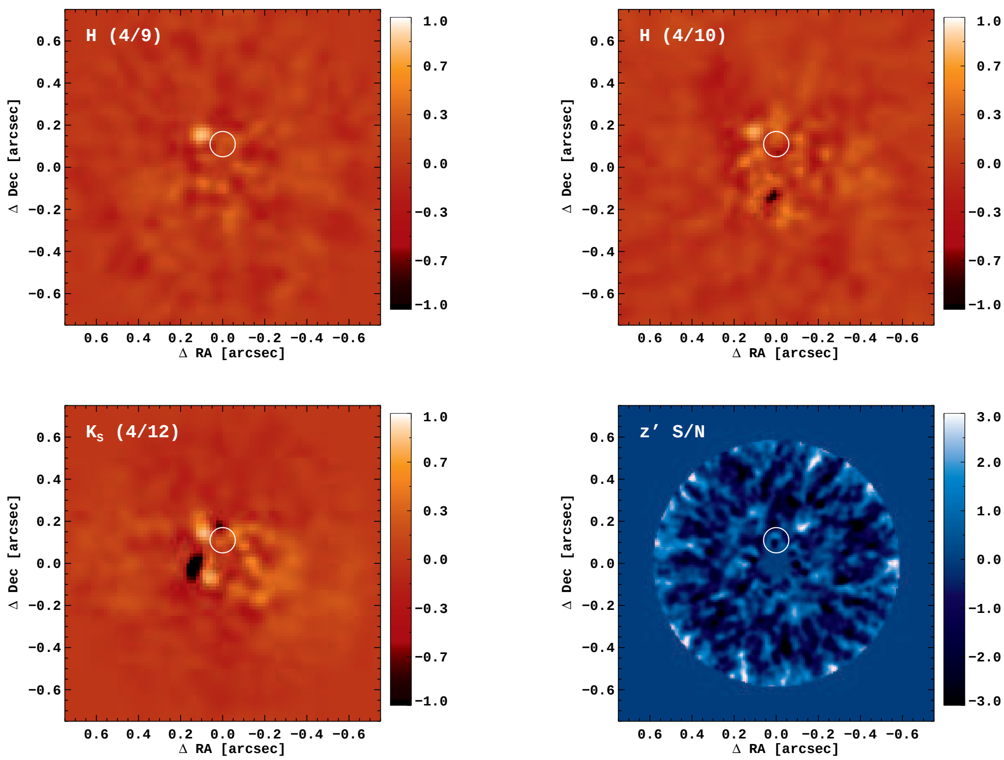

Fig. 2.— Top left and right : H band April 2014 MagAO CLIO-2 images over two consecutive nights, bottom left: K band April 2014 MagAO CLIO-2 image, bottom right: z' band April 2014 MagAO VisAO image. All images have been reduced with PCA. The position of the L' pointlike feature is circled.

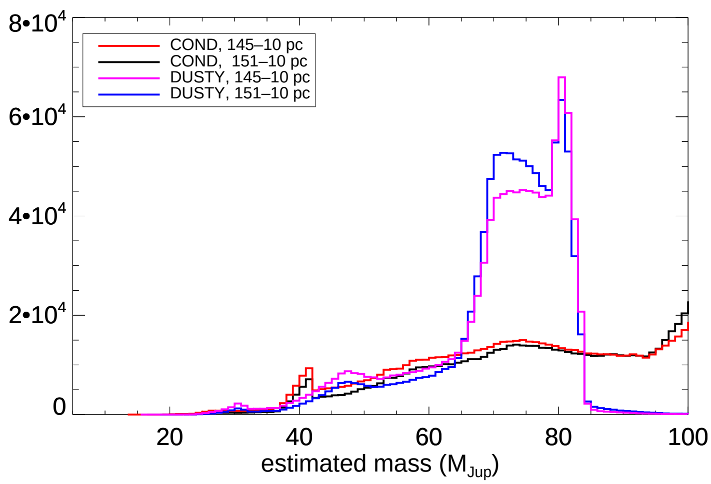

Fig. 3.— Mass estimate histogram for the pointlike feature observed in L'. If due to photospheric emission from a companion, this object would have mass >40 M_{Jup} and an easily detected H and Ks counterpart.