Near-infrared detection and characterization of the exoplanet HD 95086 b with the Gemini Planet Imager

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ABSTRACT

HD 95086 is an intermediate-mass debris-disk-bearing star. VLT/NaCo 3.8 μm observations revealed it hosts a 5 ± 2 M_Jup companion (HD 95086 b) at 0.56 AU. Follow-up observations at 1.66 and 2.18 μm yielded a null detection, suggesting extremely red colors for the planet and the need for deeper direct-imaging data. In this Letter, we report H-(1.7 μm) and K_s-(2.05 μm) band detections of HD 95086 b from Gemini Planet Imager (GPI) commissioning observations taken by the GPI team. The planet position in both spectral channels is consistent with the NaCo measurements and we confirm it to be comoving. Our photometry yields colors of H-L = 3.6 ± 0.1 mag and K_s-L = 2.4 ± 0.7 mag, consistent with previously reported 5-σ upper limits in H and K_s. The photometry of HD 95086 b best matches that of 2M 1207 b and HR 8799 cde. Comparing its spectral energy distribution with the BT-SETTL and LESIA planet atmospheric models yields T_{eq} = 700–1500 K and log g ∼ 2.1–4.5. Hot-start evolutionary models yield M = 5 ± 2 M_Jup. Warm-start models reproduce the combined absolute fluxes of the object for M = 4–14 M_Jup for a wide range of plausible initial conditions (S_0 = 8–13 kg/atom). The color–magnitude diagram location of HD 95086 b and its estimated T_{eq} and log g suggest that the planet is a peculiar L–T transition object with an enhanced amount of photospheric dust.

Key words. planets and satellites: atmospheres – planets and satellites: detection – stars: individual: HD 95086 – instrumentation: adaptive optics

1. Introduction

HD 95086 b is a directly imaged planet (5 ± 2 M_Jup, a_{phot} = 55.7 ± 2.5 AU) discovered by Rameau et al. (2013a) in L′ (3.8 μm) with VLT/NaCo (Lenzen et al. 2003; Rouset et al. 2003) orbiting the young A8 star HD 95086 (5 ± 1 M_⊙), a member of the Lower Centaurus Crux subgroup (17 ± 4 Myr, Pecaut et al. 2012; Meshkat et al. 2013). Additional L′ images taken later in 2013 confirmed that the object is comoving with its star (Rameau et al. 2013b).

NaCo Ks (2.18 μm) and NICI (Chun et al. 2008) H-band (1.65 μm) observations failed to reveal the planet (Rameau et al. 2013a; Meshkat et al. 2013). However, 5σ lower limits of Ks-L′ = 1.2 ± 0.5 mag and H-L′ = 3.1 ± 0.5 mag suggest that the planet may have extremely red colors, similar to the young planets HR 8799 b, c, and d and 2M 1207 b (Chauvin et al. 2004; Marois et al. 2008, 2010a) which have very dusty/cloudy atmospheres (Barman et al. 2011; Currie et al. 2011). Higher contrast near-IR data able to detect HD 95086 b can provide better comparisons with these objects and better constrain its atmosphere.

In this Letter, we present detections of HD 95086 b with the recently installed Gemini Planet Imager (GPI, Macintosh et al. 2014) on Gemini South from public data as a part of GPI commissioning observations (Perrin et al. 2014). The data (acquired and reduced by the GPI team), their analysis, and the detections presented in Sect. 2. In Sect. 3, we combine GPI H and K_s photometry with NaCo L′ photometry to constrain the physical properties of HD 95086 b.

2. Observations and data reduction

The GPI is a new instrument for imaging and characterizing planets around young nearby bright stars, combining an extreme adaptive optics system, coronagraphs, and an integrated field spectrograph (IFS). The IFS platescale is 14.3 ± 0.3 mas/pixel for a 2.8′′ field-of-view (FOV) and the true North position angle is given within 1 deg.

The HD 95086 spectral data were obtained at H (1.5–1.8 μm, R = 44–49) and K_s (1.9–2.19 μm, R = 62–70) in 2013 December using apodized Lyot coronagraphs (Table 1) and angular differential imaging (ADI, Marois et al. 2006a). Conditions were good: 0.43″ and 0.6″ DIMM seeing, air masses of 1.32 and 1.34, and coherence times of 19 ms and 17 ms, respectively. The GPI commissioning team used their pipeline for bad-pixel removal, destriping, non-linearity and persistence corrections, flat-fielding, wavelength calibration, and converting the data into spectral data cubes. We used the data cubes relying on the GPI pipeline quality. The data are made of 21 and 17 spectral

* Based on public data taken at the GPI commissioning.

http://planetimager.org/
cubes at $H$ and $K_1$ bands, respectively, consisting of 37 spectral channels each.

To further process the data, we registered each slice of the spectral cubes using the barycenter of the four satellite spots (attenuated replica of the central star PSF induced by a grid placed in a pupil plane, Marois et al. 2006b). Then, we minimized the speckle noise in each slice using independent pipelines each adopting various methods (Marois et al. 2006a; Lafrenière et al. 2007; Lagrange et al. 2010; Boccaletti et al. 2012; Chauvin et al. 2012; Soummer et al. 2012; Currie et al. 2013; Marois et al. 2014) used for ADI and spectral differential imaging (SSDI, Racine et al. 1999). Finally, all slices were mean-combined to yield an integrated broad-band image to maximize the signal-to-noise ratio (S/N) of any off-axis source. Binning images in wavelength and suppressing the speckles (ADI), or suppressing the speckles in each spectral channel (ADI/ADI+SSDI) and binning images give similar results, and all our pipelines recover HD 95086 b, which is the sole bright spot at the expected separation. Thus, we provide the first detections at $H$ and $K_1$ bands (Fig. 1) with an S/N of \( \sim 3 \)–4 and 5–6, respectively. The central bright speckles are masked up to 500 mas. These are the first detections of HD 95086 b with an instrument that is not NaCo/VLT. No spectrum can be extracted given the low S/N.

To estimate the planet flux and position, we needed unsaturated GPI PSFs. As GPI cannot acquire off-axis observations of the star, we calibrated photometry and astrometry using the satellite spots, which are expected to have same shape and brightness for a given filter. In the laboratory the spot-to-central-star flux ratios were \( 2.035 \times 10^{-4} \) (9.23 mag) and \( 2.695 \times 10^{-4} \) (8.92 mag) at $H$ and $K_1$ bands\(^1\). To check these values, we compared $H$ and $K$ photometry of HD 8049 B (VLT/ NAO-C SINFONI, Zurlo et al. 2013) with our measurements derived from public GPI HD 8049 data. Assuming that the object is not photometrically variable with time and considering the laboratory spot contrasts, GPI and VLT photometry are consistent within $\epsilon_1 = 0.2$ mag, which we take as the error on the ratios. From these ratios, we assessed biases induced by our processing by injecting fake point-sources (i.e., unsaturated PSFs) into the data before applying speckle-suppression techniques (Lagrange et al. 2010; Marois et al. 2010b; Chauvin et al. 2012; Galicher et al. 2012). We obtained templates of the planet image. Adjusting the flux of the templates, we found the planet photometry and the fitting error $\epsilon_2$, which depends on the detection quality. $\epsilon_2$ is 0.8 mag and 0.3 mag at $H$ and $K_1$. Finally, we estimated the variation $\epsilon_3$ of stellar flux over the sequence with the variation of spot flux. $\epsilon_3$ is 0.2 mag and 0.3 mag over the $H$ and $K_1$ sequences including the variations between spots. The resulting photometric error is the quadratic error, which is dominated by the low S/N at $H$ and is a mix of all errors at $K_1$.

For the astrometric error, we considered uncertainties in the centroiding accuracy of individual slices (\( \leq 0.3 \) pixel), the plate scale (0.02 pixel), the planet template fit (0.7 pixel at $H$, 0.5 pixel at $K_1$), and the North position angle (1 deg). The error is dominated by the low S/N of the detections and the generic GPI calibrations. The current precision is good enough to assess the comoving status of the companion (Fig. 2). We tried to use the astrometric standard HD 8049 B in GPI data to better constrain the North orientation. We did not succeed because of the high orbital motion of HD 8049 B and because there is no contemporary observation from other instruments.

### Table 1. Observing log of HD 95086 with GPI.

| Date      | Filter | Coro mask diam (mas) | DIT(s) × NDITS × Nb | Nb images | FOV rotation (°) |
|-----------|--------|----------------------|---------------------|-----------|------------------|
| 2013/12/10| $K_1$-coro | 306                  | 119.29278 × 1 × 37  | 17        | 11.7             |
| 2013/12/11| $H$-coro  | 246                  | 119.29278 × 1 × 37  | 21        | 15.0             |

Notes. Date, filter, occulting mask diameter, exposure, numbers of coadds, of spectral channels, of images, and FOV rotation.

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\(^1\)To check these values, we compared $H$ and $K$ photometry of HD 8049 B (VLT/ NAO-C SINFONI, Zurlo et al. 2013) with our measurements derived from public GPI HD 8049 data. Assuming that the object is not photometrically variable with time and considering the laboratory spot contrasts, GPI and VLT photometry are consistent within $\epsilon_1 = 0.2$ mag, which we take as the error on the ratios. From these ratios, we assessed biases induced by our processing by injecting fake point-sources (i.e., unsaturated PSFs) into the data before applying speckle-suppression techniques (Lagrange et al. 2010; Marois et al. 2010b; Chauvin et al. 2012; Galicher et al. 2012). We obtained templates of the planet image. Adjusting the flux of the templates, we found the planet photometry and the fitting error $\epsilon_2$, which depends on the detection quality. $\epsilon_2$ is 0.8 mag and 0.3 mag at $H$ and $K_1$. Finally, we estimated the variation $\epsilon_3$ of stellar flux over the sequence with the variation of spot flux. $\epsilon_3$ is 0.2 mag and 0.3 mag over the $H$ and $K_1$ sequences including the variations between spots. The resulting photometric error is the quadratic error, which is dominated by the low S/N at $H$ and is a mix of all errors at $K_1$.

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### Fig. 1. Final images of the HD 95086 system at $H$ (top) and $K_1$ (bottom) bands from two of our pipelines. The planet (arrow) is detected in all images. The bright speckles are masked up to 500 mas from the central star.

### Fig. 2. HD 95086 b positions from its star in RA ($\Delta$α) and Dec ($\Delta$δ). GPI and NaCo measurements are marked in blue and expected positions of a background object in yellow.
and Lederer, deriving the L and filter transmissions, and a spectrum of Vega. HD 95086 b lies at applying correction factors derived from published spectra, the L flux-calibrate HD 95086) by comparing ND and unsaturated 2 Correction factors from the GPI Absolute magnitudes were derived from the contrast ratios (Leggett et al. 2010, 2013), and LYON evolutionary tracks of HD 95086 b (yellow star) and data from Bonnefoy et al. (2013), and LYON evolutionary tracks (Chabrier et al. 2000; Baraffe et al. 2003) generated for the GPI/NaCo passbands.

We converted the GPI measurements into H photometry by applying correction factors derived from published spectra, the filter transmissions, and a spectrum of Vega. HD 95086 b lies at the L−T transition in this diagram, similar to other young (8–30 Myr) planets like HR 8799 cde (Marois et al. 2008, 2010a) and 2M1207 b (Chauvin et al. 2004). Its red H − L′ color compared with the sequence of field dwarf objects (Leggett et al. 2010, 2013) suggests a high content of photospheric dust (Barman et al. 2011; Currie et al. 2011), owing to reduced surface gravity (e.g. Fig. 11 of Marley et al. 2012).

We built the 1.5−4.8 μm spectral energy distribution (SED) of the planet following Bonnefoy et al. (2013) by combining the GPI photometry with the L′ one. The normalized SED (at L′) is best compatible with the young exoplanets HR 8799 bcde and 2M1207 b, but is redder. Its colors are also ~1 mag redder than those of the benchmark dusty L6.5−L7.5 field dwarf 2MASS J22443167+2043433 (Dahn et al. 2002; Stephens et al. 2009).

We also compared the SED of HD 95086 b with the predictions from grids of synthetic spectra for BT-SETTL (Allard et al. 2012) and LESIA atmospheric models (Baudino et al. 2014). Each synthetic SED was normalized to that of HD 95086 b at L′. The BT-SETTL grid covers 400 K ≤ Teff ≤ 3500 K with 50 to 100 K increments, −0.5 ≤ log g ≤ 0.6 dex with 0.5 dex increments, and M/H = 0.0 or +0.5 dex. The BT-SETTL models that reproduce the photometry of HD 95086 b have 600 K ≤ Teff ≤ 1500 K and 3.5 dex ≤ log g ≤ 4.5 dex. The three LESIA grids assume 700 K ≤ Teff ≤ 2100 K, 2.1 ≤ log g ≤ 4.5 dex, and solar abundances: one without clouds and two with clouds of Fe and Mg2SiO4 particles. For each LESIA model, we selected the planet radius that minimizes χ² between the observed and calculated apparent magnitudes. We only kept models with a radius in a realistic range derived from evolution models (0.6 to 2 Jupiter radii, Mordasini et al. 2012). All LESIA models that reproduced the HD 95086 b photometry have 900 K ≤ Teff ≤ 1500 K and 2.1 dex ≤ log g ≤ 4.5 dex.

The planet mass cannot be derived from the atmosphere models, and evolutionary models are needed. Comparing the planet’s L′ luminosity with hot-start DUSTY and COND models for an age of 17 ± 4 Myr, we find a planet mass of M = 5 ± 2 M_Jup (Table 3). We did not use the H and K1 photometries because they are poorly reproduced by the models for an object at the L−T transition (larger uncertainties than for L′). The models predict Teff and log g, in agreement with those derived from the SED fit.

Alternatively, we used the warm-start models (Spiegel & Burrows 2012) to account for possible different initial conditions for the planet (parameterized by the initial entropy between 8 and 13 k_b/gyr). The models assume solar metallicity and atmospheres enriched by a factor of 3 with/without dust clouds as boundary conditions. Synthetic SEDs are generated from predicted spectra of planets. For the full range of initial entropies we considered, models assuming masses of 4−14 M_Jup

Table 3. Physical parameters predicted by hot-start evolutionary models for the observed absolute magnitudes.

| Model         | BT-SETTL | Lesia | Dusty | L ′ |
|---------------|----------|-------|-------|-----|
| Teff (K)      | 1050±450 | 1200±300 | 916±65 | 1108±65 |
| log g (dex)   | 4.0±0.5  | 3.3±1.2  | 3.8±0.1 | 3.9±0.1 |
| M (M_Jup)     | –        | –      | 4.5    | 5.5±1.5 |

Notes. See text for details.

Final measurements are presented in Table 2. We include revised 2012 NaCo L′ photometry obtained by 1) better calibrating the planet signal (as in Currie et al. 2013) and 2) precisely deriving the L′ neutral density (ND) filter throughput (used to flux-calibrate HD 95086) by comparing ND and unsaturated β Pic data.

3 Characterization

Absolute magnitudes were derived from the contrast ratios (Table 2): MH = 15.29 ± 0.91 mag, MK1 = 14.11 ± 0.51 mag, and ML′ = 11.44 ± 0.22 mag using the 2MASS and WISE W1 (Cutri et al. 2003, 2012) photometry of the star.

Combining the H band GPI data with revised NaCo L′ data, we compared the L′/H = L′ color–magnitude diagram position of HD 95086b with that of young companions, field dwarfs (Leggett et al. 2010, 2013), and LYON evolutionary tracks (Chabrier et al. 2000; Baraffe et al. 2003) generated for the GPI/NaCo passbands.

We converted the GPI measurements into H photometry by applying correction factors derived from published spectra, the filter transmissions, and a spectrum of Vega. HD 95086b lies at

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2 Correction factors from the GPI/NaCo and 2MASS/WISE photometry, derived from the spectrum of an A7III star in the Pickles et al. (1998) library, are negligible.

3 http://phoenix.ens-lyon.fr/simulator/index.faces

4 http://www.astro.princeton.edu/~burrows/warmstart/spectra.tar.gz
match the SED of HD 95086 b (Fig. 4). For much of this range ($S_{\text{init}} = 9.5 \pm 13$) a mass of $4 \, M_{\text{Jup}}$ is favored.

4. Conclusions

We reported the near-IR detections of HD 95086 b from GPI public commissioning data. We confirmed that the companion is comoving with HD 95086 and derived the first estimates of its magnitudes with respect to its star: $H = 13.1 \pm 0.9$ and $K_1 = 12.1 \pm 0.5$.

While the mid-IR luminosity of HD 95086 b is best consistent with an $L$–$T$ transition object, it has redder near-IR colors than other young, imaged planet-mass companions. This is consistent with a very dusty and low surface gravity atmosphere.

Comparison with atmosphere models provided $600 \, K \leq T_{\text{eff}} \leq 1500 \, K$ and $2.1 \, $dex $\leq \log g \leq 4.5 \, $dex. Evolutionary models are consistent with a mass of $5 \pm 2 \, M_{\text{Jup}}$. However, the models are affected by systematic errors that are difficult to quantify because of the lack of young objects at the $L$–$T$ transition.

More higher-precision spectroscopic and photometric data for HD 95086 b are required to refine the planet properties.

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