DIRECT IMAGING AND SPECTROSCOPY OF A CANDIDATE COMPANION BELOW/NEAR THE DEUTERIUM-BURNING LIMIT IN THE YOUNG BINARY STAR SYSTEM, ROXs 42B

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ABSTRACT

We present near-infrared high-contrast imaging photometry and integral field spectroscopy of ROXs 42B, a binary M0 member of the 1–3 Myr old ρ Ophiuchus star-forming region, from data collected over 7 years. Each data set reveals a faint companion—ROXs 42Bb—located ~1′′.16 (rproj ≈ 150 AU) from the primaries at a position angle consistent with a point source identified earlier by Ratzka et al.. ROXs 42Bb’s astrometry is inconsistent with a background star but consistent with a bound companion, possibly one with detected orbital motion. The most recent data set reveals a second candidate companion at ~0′′.5 of roughly equal brightness, though preliminary analysis indicates it is a background object. ROXs 42Bb’s H and Ks band photometry is similar to dusty/cloudy young, low-mass late M/early L dwarfs. K band VLT/SINFONI spectroscopy shows ROXs 42Bb to be a cool substellar object (M8–L0; Teff ≈ 1800–2600 K), not a background dwarf star, with a spectral shape indicative of young, low surface gravity planet-mass companions. We estimate ROXs 42Bb’s mass to be 6–15 MJ, either below the deuterium-burning limit and thus planet mass or straddling the deuterium-burning limit nominally separating planet-mass companions from other substellar objects. Given ROXs 42b’s projected separation and mass with respect to the primaries, it may represent the lowest mass objects formed like binary stars or a class of planet-mass objects formed by protostellar disk fragmentation. The latter slightly blurring the distinction between non-deuterium-burning planets like HR 8799 bcde and low-mass, deuterium-burning brown dwarfs.

Key words: planetary systems – stars: individual (ROXs 42B)

Online-only material: color figures

1. INTRODUCTION

In the last decade, high-contrast direct imaging observations of young stars have provided a way to identify, confirm, and study the properties of self-luminous planet-mass companions around nearby stars undetectable by radial-velocity and transits (e.g., Chauvin et al. 2004; Marois et al. 2008, 2010; Lagrange et al. 2010; Lafrenière et al. 2008, 2010; Currie et al. 2012a; Kalas et al. 2008; Ireland et al. 2011; Carson et al. 2013; Rameau et al. 2013). These companions are typically found at wide (r ~ 25–300 AU) separations. Besides Fomalhaut b (M < 2 MJ; Currie et al. 2012a), they have super Jovian (M ≈ 4–15 MJ) masses. Thus, these objects significantly challenge even advanced models for forming them as planets (by core accretion or disk instability) or as very low-mass binary companions (e.g., Kenyon & Bromley 2009; Kratter et al. 2010; Boss 2011).

Thus far, these companions can be divided into two groups: (1) low companion-to-star mass ratio objects like HR 8799 bcde and β Pic b comprising the extrema of a population extending to planets detected by radial-velocity and plausibly formed by core accretion and (2) high-mass ratio companions (e.g., GSC 06214B) comprising the tail of a population extending up to brown dwarf masses (M ≳ 13–15 MJ) and formed by other means (Currie et al. 2011; Janson et al. 2012). Some companions have a more ambiguous nature due to their uncertain ages (and, thus, uncertain masses/mass ratios, e.g., Carson et al. 2013). Companions with well-defined ages could better probe the extremes of these populations, clarifying or blurring the distinction between bona fide planets and the lowest mass brown dwarfs.

In this Letter, we report direct imaging and spectroscopy of a candidate 6–15 MJ, companion to ROXs 42B, a binary M star and likely member of the ρ Ophiuchus star-forming region, that may add to the list of rare wide separation, young imaged planet-mass companions.

2. BASIC SYSTEM PROPERTIES AND DATA

ROXs 42B was originally identified as an M0, possibly X-ray emitting star (Bouvier and Appenzeller 1992)7 and member of the 1–3 Myr ρ Ophiuchus star-forming region (Luhman & Rieke 1999; Wilking et al. 2008; Erickson et al. 2011) located between the L1888 and L1989N S clouds. Lunar occultation measurements showed it to be a close binary (r ~ 0′′.05; Simon et al. 1995) where the brighter (M0) component contributes two-thirds of the system brightness (Ratzka et al. 2005). Sensitive optical to (sub)millimeter data reveal no clear evidence for circumstellar gas or dust (e.g., Cieza et al. 2007; Andrews and Williams 2007).

We initially identified a candidate third member of the ROXs 42B system located at a projected separation of ~1′′.16 as a

7 M0V spectroscopic standards used at the time of ROXs 42B’s discovery draw from many sources (http://www.pas.rochester.edu/~emamajek/sp/M0V.txt). Uncertainties in which calibrator was used for ROXs 42B imply a conservative spectral type range of K5–M1 (E. Mamajek 2013, private communication).
part of a general search for planet/brown dwarf companions in archival Keck, Subaru, and Very Large Telescope (VLT) data (Currie et al. 2012b, 2013b). As we later found, Ratzka et al. (2005) identified the same third member as a point source from speckle imaging data obtained in 2001. Although they did not estimate the object’s mass, their $K$ band flux ratio (0.002 ± 0.001) implied a mass below the deuterium-burning limit given the age and distance of ρ Oph and standard hot star planet evolution models (e.g., Baraffe et al. 2003; Spiegel & Burrows 2012), spurring us to rereduce additional archival data to confirm or reject its status as a bound companion and determine from multiwavelength photometry and spectroscopy whether its spectral energy distribution is consistent with those for other young directly imaged planetary-mass companions (e.g., Lafrenière et al. 2008, 2010; Currie et al. 2011; Barman et al. 2011).

Our combined data set (Table 1) includes Keck/NIRC2 and Subaru/CIAO near-infrared (near-IR) imaging and VLT/SINFONI integral field spectroscopy (IFS) and astrometry from Ratzka et al. (2005). The Keck/NIRC2 and Subaru/CIAO data we consider were taken in three epochs between 2005 and 2011 in the $H$, $K$, or $K_s$ broadband filters. The first Keck epoch data and CIAO data were obtained with (extremely) modest adaptive optics corrections, while the 2011 Keck and VLT data we consider were taken in three epochs between 2005 April 16 and 2011 June 22.

| UT Date       | Program ID  | Telescope/Camera | Filter | $t_{\text{un}}$ | $N_{\text{images}}$ | $\Delta$ | $r$ | P.A. |
|---------------|-------------|------------------|--------|-----------------|---------------------|---------|-----|------|
| 2001 Jul 01   |             | NTT/SHARP-I      | K      | ...             | ...                 | 6.74 ± 0.54 | 1.137 ± 0.014 | 268.0 ± 0.3 |
| 2005 Apr 16   | U55N2       | Keck/NIRC2       | K      | 7.5             | 6                   | 6.30 ± 0.15 | 1.157 ± 0.010 | 268.88 ± 0.60 |
| 2008 Jul 19   | S08A-074    | Subaru/CIAO      | $K_s$  | 9.9             | 5                   | 6.10 ± 0.20 | 1.160 ± 0.010 | 269.67 ± 1.00 |
| 2011 Jun 22   | H242N2      | Keck/NIRC2       | $H$    | 10              | 8                   | 6.86 ± 0.05 | 1.169 ± 0.005 | 269.65 ± 0.25 |
| 2012 Aug 11   | 089.C-0411(A)| VLT/SINFONI       | $K$ IFS| 20              | 3                   | 6.2 ± 0.2 | 1.15 ± 0.03 | 270 ± 2 |

Notes.  
* * *  
*a* Presented in Ratzka et al. (2005).  
*b* Data we present for the first time.

Using the EsoRex pipeline, we reduced the SINFONI IFS data, performing sky subtraction, combining the data into a spectroscopic cube, correcting for differential atmospheric refraction and curvature in the spectra. We extracted the spectra using a three pixel radius annulus using QFitsView. We applied the same reduction and extraction routine to a B9 telluric standard star observed during the same night at similar airmass and with the same instrumental set up. Its extracted spectrum was divided by a blackbody curve according to its effective temperature and its Brackett-$γ$ absorption feature at $\lambda \approx 2.16 \mu m$ replaced by a straight line along the continuum. Finally, we divided the extracted spectra of ROXS 42B and ROXS 42Bb by the corrected telluric standard.

Figure 1 displays each final image from our photometric data and the collapsed cube from the VLT/SINFONI spectroscopy, revealing a candidate companion, ROXS 42Bb, at $r = 1.′15–1.′17$ (labeled or denoted with an arrow, 3 o’clock position in each panel) at a signal-to-noise ratio greater than 5. Assuming a distance of 135 pc (Mamajek 2008), this angular separation corresponds to a projected physical separation of $\approx 150$ AU. Furthermore, the $H$ band 2011 data set reveal a second candidate at $r \approx 0.′5$ ($\approx 65$ AU), which has roughly the same brightness as ROXS 42Bb. The data quality in the other epochs is not sufficient to recover this object. We do not resolve the two primary stars in any data set.

3. ANALYSIS

3.1. Astrometry

We use Gaussian fitting (the IDL Astrolib subroutine gcndr3d.pro) to determine the position of ROXS 42Bb in each photometric data set, assuming a FWHM equal to that estimated for the star, and the DAOFIND centroiding routine for the SINFONI IFS data. For NIRC2 astrometric calibration, we adopt the pixel scale and north position angle offset (9.952 ± 0.005, 269.014 ± 0.005) at a signal-to-noise ratio greater than 5. Assuming a distance of 135 pc (Mamajek 2008), this angular separation corresponds to a projected physical separation of $\approx 150$ AU. Furthermore, the $H$ band 2011 data set reveal a second candidate at $r \approx 0.′5$ ($\approx 65$ AU), which has roughly the same brightness as ROXS 42Bb. The data quality in the other epochs is not sufficient to recover this object. We do not resolve the two primary stars in any data set.

Figure 2 (left panel) compares ROXS 42Bb’s astrometry derived from CIAO and NIRC2 data to the motion expected for a background object assuming a parallax of 7.4 mas. We
Figure 1. Images of ROXs 42B from 2011 $H$ band NIRC2 data (top-left), 2012 VLT/SINFONI $K_s$ band IFS data (top-right, collapsed cube shown), 2005 $K$ band Keck/NIRC2 data (bottom-left), and 2008 Subaru/CIAO data (bottom-right). The 2011 NIRC2 and 2012 SINFONI data are not smoothed; the older data sets are convolved with a Gaussian kernel equal to the image FWHM of the primary star. All images are rotated “north-up.”

(A color version of this figure is available in the online journal.)

Figure 2. Left: ROXs 42Bb’s astrometry (black squares) from 2001 to 2011 and between just the two Keck/NIRC2 epochs (overplotted green squares) is inconsistent with a background star’s motion (red squares). Right: ROXs 42Bb’s $H$/$H$-$K_s$ position is consistent with cloudy/dusty, L type low surface gravity/mass substellar objects.

(A color version of this figure is available in the online journal.)
adopt the UCAC4 (Zacharias et al. 2012) catalog’s proper motion for ROXs 42B: \( \mu_\alpha \cos(\delta), \mu_\delta = -5.9 \pm 1.6 \text{ mas yr}^{-1}, -14.1 \pm 1.8 \text{ mas yr}^{-1} \). The motion vector predicted for a background star is inconsistent with ROXs 42B’s measured astrometry. The predicted change in position between 2005 and 2011 is \( \Delta(\alpha, \delta) \approx [40 \text{ mas}, 100 \text{ mas}] \) while our astrometry is nearly consistent with no motion at all: the Keck data alone reject a background star hypothesis at more than the 5\( \sigma \) level. The 2012 SINFONI data are undersampled such that deriving \( M \) \( \sim \) 1.15 \( \pm 0.03 \) (P.A. \( \sim 270^\circ \pm 2^\circ \)) is consistent with the 2011 Keck astrometry.

A free-floating substellar object at the location of ROXs 42Bb with a similar space motion would be a rare occurrence. Even assuming twice as many young stellar objects as listed in Wilking et al. (2008) in \( 29 \text{ deg}^2 \) area covering \( \rho \) Oph and 10 times as many substellar objects as stellar members instead of an equal amount (Marsh et al. 2010) or five times fewer (Muzic et al. 2012) and that all objects have proper motions indistinguishable from ROXs 42B, the probability of contamination on the \( 10'' \times 10'' \) Keck/NIRC2 field is \( \sim 5 \times 10^{-3} \).

Although astrometry obtained with the same instrument set up (the 2005 and 2011 NIRC2 data) is formally consistent with no motion considering errors, the astrometric drift from epoch to epoch is also consistent with orbital motion. Between the two Keck/NIRC2 epochs (\( \Delta t \approx 6 \) yr), ROXs 42Bb changes position by \( \approx 0.0197 \), yielding an apparent space motion of \( \approx 3.2 \text{ mas yr}^{-1} \). For a planet at 150 AU on a circular orbit with a primary mass of \( 1 \) M\( _\odot \), the mean positional change can be up to 3.8 mas yr\(^{-1} \) for a face-on orbit. While the relative positional changes for ROXs 42Bb suggests its orbit may not be viewed face-on, the object could be near periastron, admitting a larger apparent motion.

### 3.2. Photometry and Spectroscopy

ROXs 42B is unsaturated in each image, has precise Two Micron All Sky Survey photometry (\( J = 9.906 \pm 0.02, H = 9.017 \pm 0.02, K_s = 8.671 \pm 0.02 \)), and is not known to be variable. Therefore, we flux-calibrated ROXs 42Bb from the primary fluxes and our contrast measurements (Table 1).

We adopt the Keck photometry to yield \( m_H = 15.88 \pm 0.05 \) and \( m_K = 15.00 \pm 0.15 \).

Following Currie et al. (2011, 2013a), we compare the near-IR photometry of ROXs 42Bb to the sample of L/T dwarfs compiled by Leggett et al. (2010) and directly imaged planet-mass companions (defined as \( M \leq 15 \) M\( J \); see values listed in Currie et al. 2013a). Prior to these analyses, we derive the extinction of \( A_v \approx 1.9 \) from comparing the primary’s V and K band photometry (see Cieza et al. 2007) to predicted values for pre-main sequence M0 stars (Pecaut et al. 2013), adopting the extinction law from Cardelli et al. (1989) with \( R_V = 3.1 \). Then we deredden the companion and derive absolute H and K band magnitudes: \( M_H = 9.87 \pm 0.05, M_K = 9.13 \pm 0.15 \).

The right panel of Figure 2 compares ROXs 42Bb to these populations. The companion’s H band luminosity is most consistent with late M to early L dwarfs. However, like planet-mass companions displayed here, it has a redder \( H - K_s \) color than the field sequence, a feature explainable by dustier atmospheres usually associated with low-mass/surface gravity objects (see Burrows et al. 2006; Currie et al. 2013b). ROXs 42Bb shares a very similar color–magnitude diagram position to GSC 06214B and USco CTIO 108B (Ireland et al. 2011; Bejar et al. 2008), two substellar objects with masses of \( \approx 6-16 \) M\( J \) and 10-15 M\( J \), respectively located in the nearby, slightly older Upper Scorpius association. If ROXs 42B is a member of \( \rho \) Oph or at least is similarly aged, it is likely lower mass than GCS 06214B and USco CTIO 108B.

Our SINFONI K band spectrum of ROXs 42Bb (Figure 3, top panels), when compared to spectra for M and L dwarfs from the Bonnefoy et al. (2013) SINFONI library, provides stronger evidence that the companion is most similar to young objects below/near the deuterium-burning limit. Its spectral shape precludes it from being a stellar companion earlier than \( \approx \) 5–MS–6 or a foreground mid L dwarf but appears consistent with at least some objects near the M/L dwarf transition.

Furthermore, ROXs 42Bb’s spectrum strongly resembles that for substellar, possibly planet-mass companions CT Cha B and AB Pic B, which have spectral types M8, and L0, respectively (Figure 3, top-right panel). Compared to GSC0847 B, which has a similar spectral type (M9.5...) but slightly higher inferred mass (15–35 M\( J \)), the ROXs 42Bb deviates at \( \lambda \approx 2-2.1 \mu \text{m} \). The spectrum deviates from the field, higher surface gravity (log\( (g) = 5-5.5 \)) L0 dwarf 2M0345.

The flatness of the K band spectrum (the \( H_2(K) \) index) at 2.17–2.24 \( \mu \text{m} \) may be a gravity/age diagnostic (e.g., Luhman et al. 2004).\(^{12} \) ROXs 42Bb’s \( H_2(K) \) index \( \sim 0.95 \), as defined in Canty et al. (2013), is smaller than all but one Bonnefoy et al. library objects, clearly distinguishable from that for objects more massive than \( M \approx 15 \) M\( J \) (bottom panel). Thus, ROXs 42Bb’s K band spectral shape provides additional evidence that the companion is young and has a low-mass/surface gravity. From properties of the best-fitting comparison spectra, we estimate the following most likely atmospheric properties for ROXs 42Bb: a spectral type of M8, and L0, a surface gravity of log\( (g) = 3.5-4.5 \), and a temperature of \( T_{\text{eff}} \approx 1800-2600 \text{ K} \).

### 3.3. Limits on the Age and Mass of ROXs 42Bb

Circumstantial evidence suggests that ROXs 42B’s age may be between that of most \( \rho \) Oph cloud members and the distributed population. ROXs 42B appears to lie very close to or along a filamentary structure defining members of the “ROXs 43A group,” a sub-clump of coeval very young stars (Makarov 2007) located just outside L1989N.\(^{12} \) ROXs 42Bb’s \( H_2(K) \) index \( \sim 0.95 \), as defined in Canty et al. (2013), is smaller than all but one Bonnefoy et al. library objects, clearly distinguishable from that for objects more massive than \( M \approx 15 \) M\( J \) (bottom panel). Thus, ROXs 42Bb’s K band spectral shape provides additional evidence that the companion is young and has a low-mass/surface gravity. From properties of the best-fitting comparison spectra, we estimate the following most likely atmospheric properties for ROXs 42Bb: a spectral type of M8, and L0, a surface gravity of log\( (g) = 3.5-4.5 \), and a temperature of \( T_{\text{eff}} \approx 1800-2600 \text{ K} \).

\( ^{12} \) See also Allers et al. (2007) for gravity-sensitive features at \( J \) and \( H \) band.

\( ^{13} \) Here, we convert from a dereddened V band magnitude of \( \approx 12.27 \) (see Cieza et al. 2007; Cardelli et al. 1989).
located close to ROXs 42B; see Carpenter et al. 2009) makes it an unlikely interloper.

We use the Spiegel & Burrows (2012) atmosphere/evolution models and AMES/DUSTY (Allard et al. 2001) atmosphere models coupled with the Baraffe et al. (2003) evolution models to estimate the masses of companions with photometry matching that of ROXs 42Bb (Figure 4, right panel). Assuming an age of ROXs 42B equal to that of the mean age for embedded regions of \( \rho \) Oph (1–2 Myr) the predicted mass for ROXs 42Bb ranges between \( M \sim 6 \, M_J \) and \( 9 \, M_J \). Assuming instead that its age is more similar to that of the lower extinction, distributed population (\( \tau \sim 3 \) Myr; Erickson et al. 2011), the mass of the companion is \( 11 \, M_J \). If ROXs 42B is an Upper Sco member, ROXs 42Bb’s estimated mass is \( \sim 13–15 \, M_J \).

Considering these analyses, we conservatively estimate a mass range for ROXs 42Bb of 6–15 \( M_J \); planet mass \( \sim 0.3 \, M_J \) if it is a bona fide member of the \( \rho \) Oph complex or at/near the deuterium-burning limit nominally separating planets from brown dwarfs if it is an interloping member of Upper Scorpius.

4. DISCUSSION

We present evidence that ROXs 42B is likely orbited by a substellar, possibly planetary-mass companion at \( r_{\text{proj}} \approx 150 \) AU. ROXs 42Bb may be valuable in clarifying (or complicating) our understanding of the formation of wide-separation planets and brown dwarfs. To illustrate, in Figure 4 (right panel) we compare ROXs 42Bb’s mass ratio to those for the sample of radial-velocity detected planets, brown dwarf companions, and directly imaged planets around HR 8799 and \( \beta \) Pic as in Currie et al. (2011).

As argued by Currie et al. (2011), a gap exists between HR 8799 bcde and \( \beta \) Pic b on one side and brown dwarf companions on the other, where the former (imaged planets) may be the high-mass ratio, wide-separation extrema of a population contiguous with RV-detected planets, Jupiter, and Saturn. Similarly, Janson et al. (2012) compared limits on the frequency of wide-separation companions around stars of different masses to the efficiency of different planet formation mechanisms, concluding that disk instability is unlikely to explain these objects. Although core accretion is inefficient at wide separations and challenged in being able to form 5–10 \( M_J \) companions, it nevertheless probably gave rise to planets like HR 8799 bcde and \( \beta \) Pic b.

As depicted in Figure 4, ROXs 42Bb may somewhat blur the division between bona fide planets and those of the lowest mass brown dwarfs (i.e., “planet-mass brown dwarfs”).

Other means may be required to shed light on the formation of wide-separation, super Jovian-mass companions (e.g., Konopacky et al. 2013). The system may be especially difficult to interpret if the second companion is likewise bound and substellar. Our preliminary analysis of additional data suggests that this “ROXs 42C” is brighter than ROXs 42Bb at \( J \) band and fainter at \( L' \), implying significantly bluer colors indicative of a background object. However, new astrometry is required to demonstrate that it is not bound to the primaries.
Figure 4. Mass estimates for ROXs 42Bb assuming the Baraffe et al. (2003) and Spiegel & Burrows (2012) luminosity evolution models (left) and its relationship to planets/brown dwarfs (right) assuming that ROXs 42B’s primary star mass is 1 $M_\odot$ ($M_{\text{pipe}} \approx 0.65 + 0.35 M_\odot$). Given the plausible age for ROXs 42Bb, its most likely mass is 6–15 $M_\oplus$; 6–11 $M_\oplus$ if it is a member of $\rho$ Oph (solid horizontal error bars) and 13–15 $M_\oplus$ if it is an Upper Sco (dashed horizontal error bars) member. ROXs 42Bb could be similar to low-mass brown dwarf companions or may fill in the gap between brown dwarfs on one side and radial-velocity and bona fide imaged planets on the other.

(A color version of this figure is available in the online journal.)

We leave these issues, a more detailed investigation of the host star properties, and further analysis of the atmosphere of ROXs 42Bb to future studies.

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