Evidence that the Planetary Candidate CVSO30c is a Background Star from Optical, Seeing-limited Data

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Received 2017 November 10; revised 2017 December 19; accepted 2017 December 22; published 2018 January 8

Abstract

We report serendipitous optical imaging of CVSO30c, an exoplanet candidate associated with the pre-main-sequence T Tauri star CVSO30 that resides in the 25 Ori stellar cluster. We perform PSF modeling on our seeing-limited optical image to remove the lights from the host star (CVSO30), allowing us to extract photometry of CVSO30c to be $g = 23.2 \pm 0.2$ (statistic) $\pm 0.1$ (systematic) and $r = 21.5 \pm 0.1$ (statistic) $\pm 0.1$ (systematic) magnitudes, respectively. This is 170 and 80 times too bright in the $g$ and $r$ bands, respectively, if CVSO30c were an L0 substellar object as suggested by previous studies. The optical/infrared colors of CVSO30c are indicative of a stellar, not substellar object, while the object’s color–magnitude diagram position is strikingly inconsistent with expected values for a low-mass member of 25 Ori. Broadband photometry for CVSO30c is instead better fit by contaminants such as a background K3 giant or M subdwarf. Our study demonstrates that optical seeing-limited data can help clarify the nature of candidate wide separation planet-mass companions in young star-forming regions.

Key words: planetary systems – planets and satellites: atmospheres – planets and satellites: detection – stars: pre-main sequence

1. Introduction

CVSO30 (or PTFO 8-8695 van Eyken et al. 2012) is an intriguing candidate exoplanet system in several aspects. First of all, it resides in the nearby and young stellar group 25 Orionis (Briceño et al. 2007). The 25 Ori stellar group has nearly 200 low-mass pre-main-sequence (PMS; confirmed photometrically and kinematically) within 1 degree of the bright B star 25 Ori in the Orion OB1 sub-association located at $\sim$330 pc. With an age of $\sim$7 Myr, the 25 Ori stellar cluster is of special interest to exoplanet studies. This is because PMS stars, especially those with ages of 10 Myr, play essential roles in our understanding of the formation and evolution of protoplanetary disks, and the planet formation process.

Follow-up studies of the 25 Ori group have been carried out by the Young Exoplanet Transit Initiative (Neuhäuser et al. 2011) and the Palomar Transient Factory by van Eyken et al. (2011), leading to the discovery of an exoplanet candidate CVSO30b. This is a $3–4$ Jovian mass exoplanet candidate transiting an M3 T Tauri star CVSO30 (van Eyken et al. 2012) with a period of 0.45 days and a separation of 0.008 au. In addition, high contrast near-infrared direct imaging with AO also yielded another 4.7 Jovian mass exoplanet candidate, CVSO30c, associated with the same host star at a separation of 662 au (Schmidt et al. 2016). If both CVSO30b and CVSO30c turn out to be true exoplanets, they can provide insights on the formation of exoplanets at wide separation. This is because wide separation exoplanets are difficult to be reconciled with the core accretion formation mechanism, and require the planet–planet scattering mechanism to explain their wide separation. One prediction from the planet–planet scattering is that while one exoplanet is scattered to a wide separation, there will be another exoplanet in the same system to migrate to very close-in orbits. The existence of a close-in exoplanet CVSO30b, and a wide separation exoplanet CVSO30c seems to match the planet–planet scattering scenario.

However, there have been challenges to the exoplanet nature of CVSO30b (Yu et al. 2015). Further simultaneous multi-band observations of CVSO30b by Onitsuka et al. (2017) also contradicted the exoplanet nature, suggesting an origin of circumstellar dust clump instead. On the other hand, the exoplanet nature of CVSO30c also needs to be examined. Here we report a serendipitous detection of CVSO30c in the optical band under seeing-limited conditions. This serendipitous optical imaging contradicts the exoplanetary candidacy as suggested by Schmidt et al. (2016). Our paper is organized as follows: We describe our observations and data reduction in Section 2. We present our analysis and results, including several tests on the exoplanet candidacy of CVSO30c using empirical colors of substellar objects, color–magnitude diagram, and synthetic spectra of substellar objects in Section 3. We discuss and conclude our results in Section 4.

2. Observation and Data Reduction

We performed high cadence time-series photometry monitoring of CVSO30 with the 3.5 m WIYN telescope³ at the Kitt Peak National Observatory in Arizona, USA. The observations were carried out by the One Degree Imager with the $48' \times 40'$ field of view and a pixel scale of $0.11$/pixel. The observations were conducted on the nights of 2017 February 3 and 4, through the NASA founded NOAO-WIYN observation program NN-Explore (PI: Lee, ID: 2017-0111). These data were acquired with the goal of detecting the transit of CVSO30b in two filters (g and r bands) to better assess whether or not the object is a planet. After observations, the data are reduced in a standard manner. The One Degree Imager Pipeline, Portal, and Archive (ODI-PPA; Gopu et al. 2014)

³ The WIYN Observatory is a joint facility of the University of Wisconsin-Madison, Indiana University, the National Optical Astronomy Observatory and the University of Missouri.

⁴ https://www.noao.edu/wiyn/ODI/
performed bias subtraction, dark subtraction, flat fielding, and bad pixel masking. ODI-PPA further aligned each of the individual exposures astrometrically, and calibrated the photometry using nearby SDSS standard star field observations.

During the photometric monitoring campaign, we noticed traces of a faint object close to the host star CVSO30 in images with seeing <0.78 in both Sloan g- and r-band images. To further strengthen our detection, we stacked several exposures using SWarp (Bertin et al. 2002) to increase the signal-to-noise ratio. This includes 3 × 120 s exposures in the g band with on-chip seeing of 0.72–0.73 and 6 × 60 s exposures in the r band with on-chip seeing of 0.75–0.79, respectively. The estimated precision of image registering is 0.03 and 0.04 for g and r bands, respectively. As the zero-point magnitudes of each individual exposure is different, we calibrate the stacked images photometrically using the Pan-STARRS Data Release 1 (Chambers et al. 2016). We only used bright (g < 20 mag and r < 21 mag), isolated stars for our calibration. During the photometric calibration, we found a systematic error at the level of 0.1 mag in both g and r bands.

After stacking, we also model and remove the host star’s light with a point-spread function (PSF). The PSF was constructed using bright and isolated stars in the stacked images using the IRAF routine PSF. With the PSF in hand, we then used GALFIT (Peng et al. 2002, 2010) to subtract the host star’s flux, yielding a clear detection of this faint object (as shown in Figure 1). We then obtained optical photometry of this faint object from the stacked images using SExtractor (Bertin & Arnouts 1996), deriving $g = 23.2 \pm 0.2$ (statistic) ±0.1 (systematic) and $r = 21.5 \pm 0.1$ (statistic) ±0.1 (systematic) magnitudes. We note that Schmidt et al. (2016) also carried out z-band observations using the lucky image technique with AstraLux on board the Calar Alto 2.2 m telescope. While they did not detect CVSO30c with AstraLux, they were able to constrain an upper limit of 20.5 mag in z band. This is consistent with our faint detection in the g and r bands.

Finally, we measured the separation of this faint object to the star CVSO30 to be 1.83 ± 0.04, with a position angle of 71°6 ± 0°8 (east from north). We note that the imager has a north position angle uncertainty of ~0°26. The separation and positional angle of this object in the optical are in good agreement with the separation of ~1°85 and the position angle of ~70° from Schmidt et al. (2016), hence confirming that this optically faint object is indeed CVSO30c.

3. Results

With the optical photometry, we can test whether the exoplanetary candidacy of CVSO30c holds. First of all, Schmidt et al. (2016) reported that this object is young and substellar, with a spectral type later than L0. For comparison, we check other known substellar objects with similar spectral types and ages. ROXs 42B, for example, has an effective temperature of ~2000 K, a spectral type of L0 ± 1, and a low gravity due to its youth (Currie et al. 2014). Another case is β Pic b, which has an effective temperature of 1600–1700 K, a spectral type of L3 or later, and also a low gravity due to

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Figure 1. Optical imaging of CVSO30c (north is up and east is to the left). Left panel: stacked images, where CVSO30c can be seen as a small blob right next to the host star. Right panel: residual images after subtracting the host star with PSF modeling. CVSO30c is indicated by the red marker.

5 https://panstars.stsci.edu
its youth (Currie et al. 2013; Morzinski et al. 2015). In addition, young, low gravity L and L/T transition objects have redder colors than their field counterparts. Therefore, the comparison to L0 is a best-case scenario for CVSO30c being a planet. The intrinsic optical and infrared colors of objects as late as L0 are well known and described in Kraus & Hillenbrand (2007). The predicted $g - J$ and $r - J$ colors are 9.2 and 6.7 mag. According to Schmidt et al. (2016), CVSO30c has $J = 19.6$ mag; assuming the object is an L0 substellar object, it should be fainter than $g = 28.8$ and $r = 26.3$ mag. However, given our measurement of CVSO30c, it is 180 (in $g$) and 70 (in $r$) times brighter than an L0 object, as suggested by Schmidt et al. (2016).

Second, we can also check whether CVSO30c resides in the 25 Ori stellar cluster using a color–magnitude diagram, by combing the optical photometry presented here and the infrared photometry in Schmidt et al. (2016). Downes et al. (2014) have identified 77 low-mass members of the 25 Ori stellar cluster spectroscopically. Their members all follow a well-defined 7 Myr isochrone from Baraffe et al. (1998) on the $I$ versus $I - J$ color–magnitude diagram. We cross-matched the catalog by Downes et al. (2014) with the PS1 DR1 catalog (Chambers et al. 2016) to retrieve $g$ and $r$ magnitudes of the cluster members. In addition to Downes et al. (2014), Suárez et al. (2017) also reported 50 low-mass members (including their positions and SDSS photometry) in the 25 Ori stellar group and

Figure 2. $g$ vs. $g - J$ and $r$ vs. $r - J$ color–magnitude diagram of the 25 Ori stellar group. We plot the spectroscopically confirmed 25 Ori stellar group low-mass members from Downes et al. (2014) and Suárez et al. (2017), marked in solid and empty circles. We also plot the isochrone by Baraffe et al. (2015), assuming a distance modulus of 7.6 mag, with ages of 8 Myr (solid line) and 5 Myr (dashed line), respectively. CVSO30c (marked in red), on the contrary to the spectroscopically confirmed low-mass members of the 25 Ori stellar group, does not follow the isochrones. This suggests that CVSO30c does not belong to the 25 Ori stellar group.
Orion OB1a sub-association, which are all codistant at 338 ± 66 pc. Color–magnitude diagrams clarify whether CVSO30c is consistent with being a low-mass member of 25 Ori. As shown in Figure 2, CVSO30c is strikingly inconsistent with the color–magnitude diagram position expected for a low-mass member of 25 Ori.

Furthermore, we can examine whether the SED of CVSO30c fits an L0 substellar object, as suggested by Schmidt et al. (2016). From the Phoenix Web Simulator, we retrieved the synthetic spectrum of an object with logg = 3.5 and effective temperature of 1600 K, as suggested by Schmidt et al. (2016). For comparison, we scaled the synthetic spectrum to match the infrared photometry, as shown in Figure 3. The results indicate that while we can match the synthetic spectrum to the infrared photometry, the optical photometry does not follow the synthetic spectrum, and is off by 5 mag in both the g and r bands. This suggests that the optical photometry of CVSO30c is in tension with the exoplanetary scenario.

4. Discussion and Conclusion

To summarize, our serendipitous optical detection and analysis of CVSO30c provides evidence against the object being a directly imaged planetary companion as proposed by Schmidt et al. (2016). Its optical/infrared color disagrees with values expected for an L0 or later substellar object from the SED library of Kraus & Hillenbrand (2007). Furthermore, the optical/infrared color–magnitude diagram position of CVSO30c is strongly inconsistent with the locus of spectroscopically confirmed low-mass 25 Ori members and with theoretical isochrones appropriate for young stars and substellar objects. Finally, CVSO30c’s broadband photometry strongly disagrees with the synthetic spectrum of a low gravity L0 model atmosphere from the BT-Settl grid.

Given the optical detection, it is intriguing to understand the inconsistency between our analysis and that from Schmidt et al. (2016). First of all, Schmidt et al. (2016) argued that the z’-band upper limit by Schmidt et al. (2016) both marked in squares. We also show the z’-band upper limit by Schmidt et al. (2016), marked by an open triangle. We compare the broadband photometry to a synthetic spectrum of a slightly reddened L0 substellar object with logg = 3.5, effective temperature of 1600 K, and Av = 0.3, as suggested by Schmidt et al. (2016). The synthetic spectrum (shown in gray) is retrieved from the Phoenix Web Simulator, adopting the BT-Settl model (Allard et al. 2012). For comparison, we scaled the synthetic spectrum to the infrared photometry of CVSO30c. While the infrared photometry is in good agreement with the synthetic spectrum of a substellar object, the optical photometry is in tension with this synthetic spectrum by 5 mag brighter in both g and r bands.

[5] https://phoenix.ens-lyon.fr/simulator/index.faces

Figure 3. Spectral energy distribution of CVSO30c. We show the optical photometry from this work and the infrared photometry from Schmidt et al. (2016), both marked in squares. We also show the z’-band upper limit by Schmidt et al. (2016), marked by an open triangle. We compare the broadband photometry to a synthetic spectrum of a slightly reddened L0 substellar object with logg = 3.5, effective temperature of 1600 K, and Av = 0.3, as suggested by Schmidt et al. (2016). The synthetic spectrum (shown in gray) is retrieved from the Phoenix Web Simulator, adopting the BT-Settl model (Allard et al. 2012). For comparison, we scaled the synthetic spectrum to the infrared photometry of CVSO30c. While the infrared photometry is in good agreement with the synthetic spectrum of a substellar object, the optical photometry is in tension with this synthetic spectrum by 5 mag brighter in both g and r bands.
near-IR data. Combined with the consistent spatial alignment between our optical detection and the infrared, we conclude that our optical detection is the same object seen by Schmidt et al. (2016) and labeled CVSO30c.

This work demonstrates that optical imaging under good seeing-limited conditions can clarify the nature of candidate, very wide-separation companions to young stars in star-forming regions. Given the large implied physical separations of these objects (hundreds of astronomical units), proper motion analyses are poorly suited to identify background stars. However, the optical/infrared colors of young planetary-mass objects significantly differ from most contaminating background sources. Such observations are also efficient. In this case, optical imaging using a 3.5 m telescope with a 2 minute integration time in g band or 1 minute in r band can already rule out a candidate planetary companion. Follow-up spectroscopic observations can then focus on candidates whose optical data do not reveal them to be background objects.

We are indebted to the referee, whose insightful comments and suggestions improved this manuscript significantly.

Based on observations at the Kitt Peak National Observatory and the National Optical Astronomy Observatory (NOAO Prop. ID: 2017A-0111; PI: Lee), which is operated by the Association of Universities for Research in Astronomy (AURA) under a cooperative agreement with the National Science Foundation.

Data presented herein were obtained at the WIYN Observatory from telescope time allocated to NN-EXPLORE through the scientific partnership of the National Aeronautics and Space Administration, the National Science Foundation, and the National Optical Astronomy Observatory.

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Figure 4. Comparison of CVSO30c broadband photometry with an K-giant and an M subdwarf. The grHK photometry are marked in red solid circles, while the z-band upper limit by Schmidt et al. (2016) is marked by a red open circle. We show the synthetic spectra of a K3 Giant from the spectral library of Pickles (1998), with an Av = 0.6, as well as a synthetic spectra of an M subdwarf with T_eff = 3800 K, log g = 5.5, Z = −2.0 from BT-Settl (Allard et al. 2012), with an Av = 0.26. Both provide a good fit to the CVSO30c broadband photometry, suggesting that it is a background star.