SIMP J013656.5+093347 Is Likely a Planetary-mass Object in the Carina-Near Moving Group

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Abstract

We report on the discovery that the nearby (≈6 pc) photometrically variable T2.5 dwarf SIMP J013656.5+093347 is a likely member of the ≈200 Myr old Carina-Near moving group with a probability of >99.9% based on its full kinematics. Our $v \sin i$ measurement of 50.9 ± 0.8 km s$^{-1}$ combined with the known rotation period inferred from variability measurements provide a lower limit of 1.01 ± 0.02 $R_{\text{Jup}}$ on the radius of SIMP 0136+0933, an independent verification that it must be younger than ≈950 Myr, according to evolution models. We estimate a field interloper probability of 0.2% based on the density of field T0–T5 dwarfs. At the age of Carina-Near, SIMP 0136+0933 has an estimated mass of 12.7 ± 1.0 $M_{\text{Jup}}$ and is predicted to have burned roughly half of its original deuterium. SIMP 0136+0933 is the closest known young moving group member to the Sun and is one of only a few known young T dwarfs, making it an important benchmark for understanding the atmospheres of young planetary-mass objects.

Key words: brown dwarfs -- planets and satellites: atmospheres -- stars: individual (SIMP J013656.5+093347) -- stars: kinematics and dynamics

1. Introduction

Young brown dwarfs near to and below the deuterium burning mass boundary have the potential to serve as benchmarks in understanding the atmospheres and fundamental properties of gas giant exoplanets, as they share similar temperatures, surface gravities, and masses (Gagné et al. 2015b; Faherty et al. 2016). As brown dwarfs cool down with time (e.g., Saumon & Marley 2008), their masses cannot be determined from effective temperatures only, and their ages must also be constrained. One of the few methods to precisely constrain the ages of brown dwarfs is to identify those that are members of young stellar associations (e.g., see Zuckerman & Song 2004; Mamajek 2016). Recent efforts have been made to identify such objects at the very low-mass end of the brown dwarf regime, using near-infrared large-area surveys (e.g., Gagné et al. 2015b; Aller et al. 2016; Schneider et al. 2017).

Because objects in the planetary-mass regime are inherently faint, only about a dozen have been discovered as of yet, most of which still require confirmation from a parallax or radial velocity measurement (e.g., Liu et al. 2013; Gagné et al. 2015a; Kellogg et al. 2016; Schneider et al. 2016).

The Carina-Near moving group was discovered and characterized by Zuckerman et al. (2006). It includes a spatially packed core of eight members and a stream of ten additional probable members more loosely distributed in XYZ Galactic coordinates. Based on a comparison of lithium abundance and X-ray luminosity of the Carina-Near members to those of other associations, Zuckerman et al. (2006) determined an age of 200 ± 50 Myr for the group.

Mamajek (2016) notes that no B- or A-type members of Carina-Near are present in Hipparcos (van Leeuwen 2007), and no systematic survey has been published since Zuckerman et al. (2006) to identify additional low-mass members. The latest-type member of Carina-Near listed by Zuckerman et al. (2006) is the M2.5 dwarf, GJ 140 C.

In this paper, we report that the variable T2.5 dwarf SIMP 0136+0933 (SIMP J013656.5+093347; Artigau et al. 2006, 2009) is a likely member of Carina-Near. The BASS-Ultracool survey that led to this discovery is summarized in Section 2. New spectroscopic observations are described in Section 3, and the full six-dimensional kinematics of SIMP 0136+0933 are discussed in Section 4. In Section 5, it is demonstrated that SIMP 0136+0933 is unlikely a random interloper from the field, and its physical properties are estimated in Section 6. Section 7 discusses the photometric variability of SIMP 0136+0933 in light of its young age. This work is concluded in Section 8.

2. The BASS-Ultracool Survey

The BANYAN All-Sky Survey-Ultracool (BASS-Ultracool; J. Gagné et al. 2017, in preparation) was initiated to locate the late-L to T-type members of young moving groups, with the aim to explore the fundamental properties of isolated planetary-mass objects with cold atmospheres ($T_{\text{eff}} \leq 1500$ K). It relies on a cross-match of large-scale red and near-infrared catalogs such as 2MASS (Skrutskie et al. 2006), AllWISE (Wright et al. 2010), and Pan-STARRS1 (Chambers et al. 2016) to identify high proper motion objects with red W1–W2 AllWISE colors, for which moving group membership is assessed with the Bayesian Analysis for Nearby Young AssociationNs II tool (BANYAN II; Gagné et al. 2014) and its successor BANYAN Σ (J. Gagné et al. 2017, in preparation). Initial discoveries from this survey include the T5.5 dwarf SDSS J111010.01+011613.1 as a
is a six-dimensional vector of coordinates in \( \mathbb{R}^6 \) in a right-handed system where \( \vec{x} \) is a six-dimensional vector representing the center of the group, \( \Sigma \) is the covariance matrix of all members, and \( [\Sigma]^{1/2} \) is the determinant of the covariance matrix. The diagonal elements of \( \Sigma \) represent variances in the \( XYZUVW \) directions, while the off-diagonal elements represent correlations between spatial and kinematic coordinates, which can be related to rotation angles in six-dimensional space. This multivariate model is a generalization of the freely rotating 3D ellipsoid models used in BANYAN II, as it allows for correlations in the spatial and kinematic coordinates. The resulting model parameters are (in order of \( XYZUVW \)):

\[
\begin{pmatrix}
\vec{x}_0 & \vec{\Sigma} \\
60.5 & -16.7 & 434.3 & 47.3 & -46.4 & 7.9 & -1.6 \\
-15.0 & 47.3 & 300.1 & -15.7 & -23.1 & -23.4 & 3.8 \\
3.8 & -46.4 & -15.7 & 10.2 & 0.5 & -0.5 & 2.0 \\
2.0 & 7.9 & -23.1 & 0.5 & 3.5 & 2.2 & 6.4 \\
6.4 & -1.6 & -23.4 & -0.5 & 2.2 & 3.8
\end{pmatrix}
\]

(2)

in units of pc and km s\(^{-1}\).

In this survey, SIMP 0136+0933 was identified as a candidate member of Carina-Near from a cross-match of 2MASS and AllWISE sources with colors redder than \( W1 - W2 = 0.6 \), which corresponds to spectral types later than \( \sim L8 \) (field dwarfs) or \( \sim L5 \) (young dwarfs; Faherty et al. 2016). This T2.5 dwarf was discovered as part of the SIMP survey (Artigau et al. 2006; Robert et al. 2016) and has been the subject of extensive photometric follow-up due to its photometric variability (e.g., see Artigau et al. 2009; Metchev et al. 2013; Radigan et al. 2014; Croll et al. 2016).

A proper motion derived from 2MASS and AllWISE alone categorized it as a high-probability (>99.9%) candidate member of the Carina-Near moving group using a preliminary version of the BANYAN \( \Sigma \) tool, with a kinematic distance (5.6 ± 0.3 pc) placing it along the sequence of known T dwarfs in near-infrared color–magnitude diagrams. Using the updated astrometry from Weinberger et al. (2016) preserved a high Bayesian membership probability of >99.9%, with a statistical radial velocity prediction of 9.4 ± 0.8 km s\(^{-1}\) if it is indeed a member of Carina-Near.
3. Observations

SIMP 0136+0933 was observed with the Near InfraRed Spectrometer (NIRSPEC; McLean et al. 2000) on the Keck II Telescope on 2013 October 16 and 2016 February 2. The first night had moderate cloud coverage with ~60% humidity and a 1″ seeing, while the second night was clear with a 0″.8 seeing. The high-dispersion cross-dispersed mode with the NIRSPEC-7 filter and the 0″.432-wide slit were used, yielding a resolving power of $\lambda/\Delta \lambda \approx 20,000$ over 2.00–2.39 μm. Two exposures of 900 s (2013 October) and 750 s (2016 February) were obtained at airmasses of 1.11 and 1.15, yielding signal-to-noise ratios of ~20 and ~13 per pixel after reduction. The AOV-type standard HD 6457 was observed immediately after SIMP 0136+0933 at a similar airmass for telluric correction. A single NeArKr calibration lamp exposure and ten 4.4 s “on” and “off” flat-field exposures were obtained at the end of each night for wavelength calibration and correction of pixel-to-pixel variations in detector response. The data were reduced with a modified version of the REDSPEC package as described in Burgasser et al. (2015).

4. The Kinematics of SIMP 0136+0933

Spectral data in order 33 (2.29–2.33 μm) were forward-modeled using the Markov Chain Monte Carlo analysis described in detail in Burgasser et al. (2016). We used the atmosphere models of Allard et al. (2012) and the telluric transmission spectrum from the Solar atlas of Livingston & Wallace (1991). Radial and rotational velocities and their uncertainties were determined by marginalizing over the Markov chains, yielding consistent results between the two epochs (differences of 0.4 and 0.1 km s$^{-1}$, respectively). Combining these values as an error-weighted average, we determine a radial velocity of 11.5 ± 0.4 km s$^{-1}$ and $v \sin i = 50.9 ± 0.8$ km s$^{-1}$ for SIMP 0136+0933.

The XYZ Galactic coordinates and UVW space velocities of SIMP 0136+0933 were calculated by adding the radial velocity measurement to the set of kinematic measurements available in the literature in a 10$^6$-elements Monte Carlo simulation that assumes Gaussian measurement errors. These values are reported in Table 2, and they place SIMP 0136+0933 at 20.9 ± 11.6 pc and 6.4 ± 1.6 km s$^{-1}$ from the core of the Carina-Near multivariate Gaussian model (the largest kinematic deviation occurs in the U direction, see Figure 1). This makes SIMP 0136+0933 a likely member of the Carina-Near stream, which is more spatially extended than its core. The second-nearest Carina-Near member to the Sun, the M2 dwarf Gl 358 (9.5 ± 0.1 pc; van Leeuwen 2007), is also a member of its stream (Zuckerman et al. 2006). At a distance of ~6.1 pc, SIMP 0136+0933 is the nearest known member of any young moving group and is among the youngest objects known to date, along with the M4+M5 EQ Peg AB system at 6.18 ± 0.06 pc (van Leeuwen 2007; Zuckerman et al. 2013), the M5 dwarf AP Col at 8.39 ± 0.07 pc (Riedel et al. 2011), and a few possibly young X-ray active mid-M dwarfs from the sample of Riaz et al. (2006; see their Table 4). SIMP 0136+0933 is also among the 100 nearest systems to the Sun.

5. Field Interloper Probability

The probability that SIMP 0136+0933 is a random field interloper was estimated with the field density of T0–T5 dwarfs measured by Reylé et al. (2010) and a synthetic population of 10$^7$ objects within 6.14 pc, drawn from the XYZUVW distribution of stars in the Galactic neighborhood using the Besançon model (Robin et al. 2012). The separation between each object and the Carina-Near multivariate Gaussian model in XYZUVW space was then calculated using the Mahalanobis distance, given by:

$$M = \sqrt{(\mathbf{x} - \bar{x}_0)^T \Sigma^{-1} (\mathbf{x} - \bar{x}_0)},$$  

Table 2

| Property | Value | Reference |
|----------|-------|-----------|
| Position and Kinematics | | |
| R.A. | 01:36:56.62 | 1 |
| Decl. | +09:33:47.3 | 1 |
| $\mu_\alpha \cos\delta$ (mas yr$^{-1}$) | 1222.70 ± 0.78 | 1 |
| $\mu_\delta$ (mas yr$^{-1}$) | 0.5 ± 1.2 | 1 |
| RV (km s$^{-1}$) | 11.5 ± 0.4 | 1 |
| Triangulometric distance (pc) | 6.139 ± 0.037 | 1 |
| X (pc) | 2.967 ± 0.018 | 1 |
| Y (pc) | 2.384 ± 0.014 | 2 |
| Z (pc) | −4.817 ± 0.029 | 2 |
| U (km s$^{-1}$) | −33.12 ± 0.26 | 2 |
| V (km s$^{-1}$) | −17.19 ± 0.20 | 2 |
| W (km s$^{-1}$) | −2.76 ± 0.32 | 2 |
| Photometric Properties | | |
| $\lambda_0$ (SDSS12) | 20.79 ± 0.06 | 3 |
| $\lambda_{AB}$ (Pan-STARRS1) | 17.33 ± 0.02 | 4$^a$ |
| $\lambda_{AB}$ (SDSS12) | 16.55 ± 0.02 | 3 |
| $\lambda_{AB}$ (Pan-STARRS1) | 15.72 ± 0.03 | 4$^a$ |
| J (2MASS) | 13.46 ± 0.03 | 5 |
| H (UKIDSS) | 12.809 ± 0.002 | 6 |
| K (UKIDSS) | 12.585 ± 0.002 | 6 |
| W1 (AlWISE) | 11.94 ± 0.02 | 7 |
| W2 (AlWISE) | 10.96 ± 0.02 | 7 |
| W3 (AlWISE) | 9.74 ± 0.05 | 7 |
| Spectroscopic Properties | | |
| Spectral type | T2.5 ± 0.5 | 8 |
| K1 at 1.169 μm (Å) | 8.6 ± 1.0 | 2 |
| K1 at 1.177 μm (Å) | 11.7 ± 1.1 | 2 |
| K1 at 1.243 μm (Å) | 5.4 ± 0.3 | 2 |
| K1 at 1.254 μm (Å) | 8.5 ± 0.3 | 2 |
| Fundamental Properties | | |
| Age (Myr) | 200 ± 59 | 9 |
| Mass (M$_{\odot}$) | 12.7 ± 1.0 | 2 |
| Radius (R$_{\odot}$) | 1.22 ± 0.01 | 2 |
| $T_{\text{eff}}$ (K) | 1098 ± 6 | 2 |
| log g | 4.31 ± 0.03 | 2 |
| log L$/$L$_{\odot}$ | −4.688 ± 0.005 | 2 |
| Rotation period (hr) | 2.425 ± 0.003 | 10$^b$ |
| $v \sin i$ (km s$^{-1}$) | 50.9 ± 0.8 | 2 |
| $i$ (°) | 55.9$^\circ$ ± 5° | 2 |

Notes:

$^a$ Average and standard deviation from five PS1 measurements. The dispersion is larger than quoted uncertainties, likely indicating that variability is also present at red-optical wavelengths.

$^b$ S. Bouchard et al. (2017, in preparation) used an improved method and ~8 hr of J-band monitoring over two nights to improve the previous measurement of 2.3895 ± 0.0005 (Artigau et al. 2009).

References. (1) Weinberger et al. (2016), (2) This work, (3) Alam et al. (2015), (4) Chambers et al. (2016), (5) Skrutskie et al. (2006), (6) Lawrence et al. (2007), (7) Kirkpatrick et al. (2014), (8) Artigau et al. (2006), (9) Zuckerman et al. (2006), (10) S. Bouchard et al. (2017, in preparation).
where $\bar{x}$, $\bar{x}_0$, and $\bar{\Sigma}$ are defined in Section 2. The Mahalanobis distance is a generalized $N\sigma$ distance that accounts for the size and orientation of the multivariate Gaussian model in six-dimensional space.

A total of 14,609 out of $10^7$ synthetic objects were found to have a Mahalanobis distance at least as small as that of SIMP 0136+0933 ($M = 3.28$). Adjusting this result to the T0–T5 field density of $2 \pm 0.3$ objects pc$^{-3}$ measured by Reylé et al. (2010), this corresponds to 4.52$^{+0.4}_{-0.3}$ expected occurrences. Based on Poisson statistics, the detection of at least one early T dwarf such as SIMP 0136+0933, thus, has a 0.2% probability of being a chance event. This analysis does not assume a young age for SIMP 0136+0933.

6. Fundamental Properties

The spectral energy distribution of SIMP 0136+0933 was built from a combination of the literature SpeX spectrum (Burgasser et al. 2008) with SDSS, Pan-STARRS1, 2MASS, and AllWISE photometry (see Table 2) and is displayed in Figure 2. The method of Filippazzo et al. (2015) was used to perform an empirical measurement of its bolometric luminosity $\log L_\odot / L_\odot = -4.688 \pm 0.005$, and the Saumon & Marley (2008) models at 200 $\pm$ 50 Myr were used to infer a radius of 1.22 $\pm$ 0.01 $R_\text{Jup}$. These properties were converted to an effective temperature using the Stefan–Boltzmann law, yielding $T_{\text{eff}} = 1098 \pm 6$ K, at the lower-end of T2–T3 field dwarf temperatures (Filippazzo et al. 2015). This is consistent with the observed trend that young brown dwarfs tend to have slightly lower effective temperatures at a given spectral type (Metchev & Hillenbrand 2006; Faherty et al. 2012; Gagné et al. 2015b).

A corresponding mass and surface gravity of $12.7 \pm 1.0 M_\text{Jup}$ and $\log g = 4.31 \pm 0.03$ were obtained from the Saumon & Marley (2008) evolutionary models. As displayed in Figure 3(a), a comparison of these values with the models of Allard et al. (2012) implies that SIMP 0136+0933 should have burned roughly half of its deuterium content. The bolometric luminosity of SIMP 0136+0933 is slightly fainter than that of average T2.5 dwarfs (Filippazzo et al. 2015), although it is located within the $1\sigma$ range of the field distribution. The $\sim$150 Myr old T4.5 dwarf, GU Psc b, is similarly fainter than the field dwarfs sequence and yields a comparable $\log L_\odot / L_\odot = -4.87 \pm 0.10$ (Filippazzo et al. 2015).
The \( v \sin i \) measurement obtained in Section 4 was combined with the rotation period of Artigau et al. (2009) to constrain the inclination of SIMP 0136+0933 to \( i = 55.9^{\pm}1.5^{\circ} \), assuming the Saumon & Marley (2008) radius at the age of Carina-Near. Without making any assumption on the age of SIMP 0136+0933, the radius of SIMP 0136+0933 can be constrained to a lower limit of 1.01 \( \pm \) 0.02 \( R_{\text{up}} \), which would correspond to it being observed equator on, or to larger radii at other inclinations. This radius lower limit can be translated to an upper age limit of 910 \( ^{+}2^{+}10 \) Myr, or an upper mass limit of 42.6 \( ^{+}2^{+}3 \) \( M_{\odot} \), based on the Saumon & Marley (2008) models and the measured bolometric luminosity (see Figure 3(b)). Adding the upper limit of this age constraint to the analysis presented in Section 5 further reduces the field interloper probability down to 0.0001%.

A preliminary analysis of the harmonics in the long-term light curve of SIMP 0136+0933, which assumes that its variability is dominated by a single spot, constrains its inclination to \( i < 60^{\circ} \) (S. Bouchard et al. 2017, in preparation). If the single-spot hypothesis can be confirmed, it will further constrain the radius to values larger than 1.17 \( \pm \) 0.02 \( R_{\text{up}} \) and a model-dependent age below 280 \( ^{+}30^{+} \) Myr, which would corroborate the Carina-Near membership and the planetary mass of SIMP 0136+0933.

The method of McLean et al. (2003) was used to measure \( K_{\text{1}} \) equivalent widths of 8.6 \( \pm \) 1.0, 11.7 \( \pm \) 1.1, 5.4 \( \pm \) 0.3, and 8.5 \( \pm \) 0.3 Å (at 1.169, 1.177, 1.243, and 1.254 \( \mu \text{m} \), respectively) from the GNIRS spectrum. These values are consistent with the field population of T2–T3 dwarfs (McLean et al. 2003), which is not unexpected given that the slightly younger T5.5 dwarf SDSS J111010.01+011613.1 (\( \sim 150 \) Myr; Gagné et al. 2015a) has \( K_{\text{1}} \) equivalent widths consistent or slightly weaker than those of field T5 dwarfs (Martin et al. 2017).

7. Variability and Age

Surface gravity is a key parameter in the description of dust behavior in brown dwarf atmospheres. Among L dwarfs, thicker cloud decks are expected among lower-gravity objects due to the slower settling rates. Thick cloud decks lead to a redistribution of the near-infrared spectral energy distribution to longer wavelengths, leading to redder infrared colors for low-gravity young objects (Faherty et al. 2016). As dust-bearing clouds of varying thicknesses are generally invoked to explain such variability, a gravity-dependence of variability behavior can be expected. Metchev et al. (2015) included a sample of low-gravity L dwarfs in the large SPITZER sample of photometric observations and found tentative indications that the low-gravity objects displayed larger photometric amplitudes, even though the fraction of variable objects appeared to be independent of surface gravity. The detection of large (7%–10%) photometric \( J \)-band variability in very low-gravity L dwarfs (PSO J318.5338–22.8603, WISEP J004701.06+680352.1; Biller et al. 2015; Lew et al. 2016) appears to corroborate these findings, as earlier surveys at these wavelengths failed to uncover >4% variability among L dwarfs.

Figure 4 compiles \( J, 3.6, \) and 4.5 \( \mu \text{m} \) variability detections in a spectral-type versus color diagram. The detections to date suggest a higher fraction of high-amplitude variables among very red L-type dwarfs, but some of these discoveries were made from surveys explicitly targeting red low-gravity objects. Overall, this tentative correlation between surface gravity and variability amplitude has yet to be set on firm statistical grounds.

Whether low-gravity T dwarfs exhibit stronger variability remains unknown, but SIMP 0136+0933 may provide the first such example with its \( \sim 1\%–\)6\% \( J \)-band variability (Croll et al. 2016). Only a handful of low-gravity T dwarfs are currently confirmed (e.g., Naud et al. 2014; Gagné et al. 2015a), none of which have reported measurements assessing their photometric variability.

8. Summary and Conclusions

This paper presents the discovery that the nearby (~6 pc) T2.5 dwarf SIMP 0136+0933 is a likely member of the 200 Myr old Carina-Near moving group, based on the new Bayesian analysis tool BANYAN \( \Sigma \) and radial velocity measurement. At this young age, SIMP 0136+0933 has a model-dependent mass of 12.7 \( \pm \) 1.0 \( M_{\odot} \) at the planetary-mass boundary. Given the tentative correlation between high-amplitude variability and youth in L dwarfs, the discovery that SIMP 0136+0933 is a member of Carina-Near indicates that such a correlation could hold in the T dwarfs regime; however, more young T dwarfs will need to be investigated for variability to verify this. SIMP 0136+0933 is an even more powerful benchmark than previously appreciated and will help to understand weather patterns in gaseous giant atmospheres.

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Figure 3. Fundamental properties of SIMP 0136+0933. Left panel: deuterium fraction left as a function of age at the brown dwarf/planetary boundary. The models of Allard et al. (2012) at the age and estimated mass of SIMP 0136+0933 suggest that it should only have partially depleted its deuterium content. Right panel: minimum radius of SIMP 0136+0933 (red triangle) obtained from \( \nu \sin i \) and rotational periods only; minimum radius when the \( i < 60^\circ \) constraint is added (purple triangle); and the models of Saumon & Marley (2008; thick colored lines).

Figure 4. Brown dwarfs with detected photometric variability as a function of spectral type and near-infrared colors. The colors of individual circles indicate the wavelength where variability is detected, and the size of the circle indicates the variability amplitude in linear scale. The polynomial relations of Faherty et al. (2016) for field and young brown dwarfs are displayed as solid and dashed lines, respectively. In the L spectral class, there is tentative evidence for high-amplitude variable brown dwarfs to be more frequent at redder near-infrared colors (Metchev et al. 2015), which are generally associated with younger low-gravity brown dwarfs. This figure was built with data from Dupuy & Liu (2012), Radigan (2014), and references therein.
J.G. wrote most of the manuscript, generated Figures 1–3(b), led the BASS-Ultracool survey and the development of the BANYAN Σ tool, and the kinematic analysis; J.K.F. led the spectral energy distribution analysis. A.B. acquired and reduced the NIRSPEC spectrum and measured the radial velocity and \( v \sin \iota \). É.A. wrote Section 7 and generated Figures 3(a) and 4. S.B. provided useful discussions on the photometric properties of SIMP 0136+0933 and unpublished photometric data. L.A. cross-matched SIMP 0136+0933 with individual epochs of the Pan-STARRS1 catalog. R.D. and D.L. participated in the development of the BANYAN Σ tool. D.C.B.G. observed the NIRSPEC spectrum.

Facility: Keck:II (NIRSPEC).

Software: BANYAN Σ, BANYAN II, Python, IDL by Harris Geospatial, Overleaf.

References

Alam, S., Albareti, F. D., Allende Prieto, C., et al. 2015, ApJS, 219, 12
Allard, F., Homeier, D., & Freytag, B. 2012, RSPTA, 370, 2765
Aller, K. M., Liu, M. C., Magnier, E. A., et al. 2016, ApJ, 821, 120
Artigau, É, Bouchard, S., Doyon, R., & Lafrenière, D. 2009, ApJ, 701, 1534
Artigau, É, Doyon, R., Lafrenière, D., et al. 2006, ApJL, 651, L57
Bardalez-Gagliuffi, D., Faherty, J. K., Burgasser, A. J., et al. 2017, ApJ, submitted
Billers, B. A., Vos, J., Bonavita, M., et al. 2015, ApJ, 813, L23
Burgasser, A. J., Blake, C. H., Gelino, C. R., Sahlmann, J., & Bardalez Gagliuffi, D. 2016, ApJ, 827, 25
Burgasser, A. J., Gillon, M., Melis, C., et al. 2015, AJ, 149, 104
Burgasser, A. J., Liu, M. C., Ireland, M. J., Cruz, K. L., & Dupuy, T. J. 2008, ApJ, 681, 579
Chambers, K. C., Magnier, E. A., Metcalfe, N., et al. 2016, arXiv:1612.05560
Croll, B., Muirhead, P. S., Lichtman, J., et al. 2016, arXiv:1609.03587
Desidera, S., Covino, E., Messina, S., et al. 2015, A&A, 573, A126
Dupuy, T. J., & Liu, M. C. 2012, ApJS, 201, 19
Faherty, J. K., Burgasser, A. J., Walter, F. M., et al. 2012, ApJ, 752, 56
Faherty, J. K., Riedel, A. R., Cruz, K. L., et al. 2016, ApJ, 825, 10
Filippazzo, J. C., Rice, E. L., Faherty, J., et al. 2015, ApJ, 810, 158
Gagné, J., Burgasser, A. J., Faherty, J. K., et al. 2015a, ApJL, 808, L20
Gagné, J., Faherty, J. K., Cruz, K. L., et al. 2015b, ApJS, 219, 33
Gagné, J., Faherty, J. K., Mamajek, E. E., et al. 2017, ApJS, 228, 18
Gagné, J., Lafrenière, D., Doyon, R., Malo, L., & Artigau, É 2014, ApJ, 783, 121
Gontcharov, G. A. 2006, Astrl, 32, 759
Gray, R. O., Corbally, C. J., Garrison, R. F., et al. 2006, AJ, 132, 161
Kellogg, K., Metchev, S., Gagné, J., & Faherty, J. 2016, ApJL, 821, L15
Kirkpatrick, J. D., Schneider, A., Fajardo-Acosta, S., et al. 2014, ApJ, 783, 122
Lawrence, A., Warren, S. J., Almaini, O., et al. 2007, MNRAS, 379, 1599
Lew, B. W. P., Apai, D., Zhou, Y., et al. 2016, ApJL, 829, L32
Lindegren, L., Lammers, U., Bastian, U., et al. 2016, A&A, 595, A4
Liu, M. C., Magnier, E. A., Deacon, N. R., et al. 2013, ApJL, 777, L20
Livingston, W., & Wallace, L. 1991, An Atlas of the Solar Spectrum in the Infrared from 1850 to 9000 cm\(^{-1}\) (1.1 to 5.4 micrometer), NSO Technical Rep. (Tucson, AZ: National Solar Observatory)
Mamajek, E. E. 2016, in IAU Symp. 314, Young Stars & Planets Near the Sun, ed. J. H. Kastner, B. Stelzer, & S. A. Metchev (Cambridge: Cambridge Univ. Press), 21
Martin, E. C., Mace, G. N., McLean, I. S., et al. 2017, ApJ, 838, 73
McLean, I. S., Graham, J. R., Becklin, E. E., et al. 2000, Proc. SPIE, 4008, 1048
McLean, I. S., McGovern, M. R., Burgasser, A. J., et al. 2003, ApJ, 596, 561
Metchev, S., Apai, D., Radigan, J., et al. 2013, AN, 334, 40
Metchev, S. A., Heinze, A., Apai, D., et al. 2015, ApJ, 799, 154
Metchev, S. A., & Hillenbrand, L. A. 2006, ApJ, 651, 1166
Naud, M.-É., Artigau, É, Malo, L., et al. 2014, ApJ, 787, 5
Norström, B., Mayor, M., Andersen, J., et al. 2004, A&A, 418, 989
Radigan, J. 2014, ApJ, 797, 120
Radigan, J., Lafrenière, D., Jayawardhana, R., & Artigau, É. 2014, ApJ, 793, 73
Reylé, C., Delorme, P., Willott, C. J., et al. 2010, A&A, 522, A112
Riaz, B., Gizis, J. E., & Harvin, J. 2006, AJ, 132, 866
Riedel, A. R., Murphy, S. J., Henry, T. J., et al. 2011, AJ, 142, 104
Robert, J., Gagné, J., Artigau, É, et al. 2016, ApJ, 830, 144
Robin, A. C., Marshall, D. J., Schultheis, M., & Reylé, C. 2012, A&A, 538, A106
Saumon, D., & Marley, M. S. 2008, ApJ, 689, 1327
Schneider, A. C., Windsor, J., Cushing, M. C., Kirkpatrick, J. D., & Shkolnik, E. L. 2017, AJ, 153, 196
Schneider, A. C., Windsor, J., Cushing, M. C., Kirkpatrick, J. D., & Wright, E. L. 2016, ApJL, 822, L1
Skrutskie, M. F., Cutri, R. M., Stiening, R., et al. 2006, AJ, 131, 1163
Torres, C. A. O., Quast, G. R., da Silva, L. L., et al. 2006, A&A, 460, 695
van Leeuwen, F. 2007, A&A, 474, 653
Weinberger, A. J., Boss, A. P., Keiser, S. A., et al. 2016, AJ, 152, 24
Wright, E. L., Eisenhardt, P. R. M., Mainzer, A. K., et al. 2010, AJ, 140, 1868
Zacharias, N., Finch, C. T., Girard, T. M., et al. 2013, AJ, 145, 44
Zuckerman, B., Bessell, M. S., Song, I., & Kim, S. 2006, ApJL, 649, L115
Zuckerman, B., & Song, I. 2004, ARA&A, 42, 685
Zuckerman, B., Vicun, L., Song, I., & Schneider, A. 2013, ApJ, 778, 5