A SUBSTELLAR COMPANION TO THE DUSTY PLEIADES STAR HD 23514

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Received 2011 August 26; accepted 2011 December 20; published 2012 March 2

ABSTRACT

With adaptive optics imaging at Keck observatory, we have discovered a substellar companion to the F6 Pleiades star HD 23514, one of the dustiest main-sequence stars known to date ($L_\text{IR}/L_\odot \sim 2\%$). This is one of the first brown dwarfs discovered as a companion to a star in the Pleiades. The $0.06 \, M_\odot$ late-M secondary has a projected separation of $\sim 360 \text{ AU}$. The scarcity of substellar companions to stellar primaries in the Pleiades combined with the extremely dusty environment make this a unique system to study.

Key words: binaries: visual -- brown dwarfs -- infrared: stars -- open clusters and associations: individual (Pleiades) -- stars: individual (HD 23514)

Online-only material: color figure

1. INTRODUCTION

HD 23514 (HII 1132) is an F6 star in the Pleiades. It is one of only a handful of youthful stars, ages 35 to $\sim 100 \text{ Myr}$, that are surrounded by warm dust particles located in the terrestrial planet zone and which absorb a percent or so of the bolometric luminosity of their central star (Melis et al. 2010). We have observed HD 23514 with the adaptive optics system at the Keck observatory using the NIRC2 camera to check the binarity of this unusually dusty star.

To the best of our knowledge during the time the images in Table 1 were obtained and analyzed, in the Pleiades no substellar companion to a stellar primary was known. However, while this paper was being reviewed, Geißler et al. (2012) reported the discovery of a substellar companion to the Pleiad HII 1348. Studies of substellar objects in the Pleiades have focused on free floating brown dwarfs or companions to low-mass stars (Stauffer et al. 2007; Lodieu et al. 2007; Bouy et al. 2006; Martin et al. 2003; Pinfield et al. 2000). With an adaptive optics survey of 144 solar-type stars in the Pleiades, Bouvier et al. (1997) were sensitive to objects with masses down to $\sim 0.03 \, M_\odot$ at separations of $\sim 1''$. However, their lowest mass companion ($\sim 0.15 \, M_\odot$) is still above the substellar boundary (they did not observe HD 23514). Our work has revealed one such substellar companion in the Pleiades.

2. OBSERVATIONS

We observed HD 23514 with the adaptive optics (AO) system and the NIRC2 narrow camera at the 10 m Keck II telescope at Mauna Kea observatory. Observations were performed in natural guide star mode. Some images were obtained in angular differential imaging (ADI) mode while others had the primary behind a 600 mas or 800 mas diameter coronographic spot. The rest of the images were taken with dithered observations in position angle (P.A.) mode where the field of view is rotated so as to keep the sky fixed on the NIRC2 camera. All of the data were reduced in the standard manner (flat fielding, dark subtraction, sky subtraction) with IRAF6 routines. The data were linearized prior to processing using an IDL program.7 We have applied the NIRC2 distortion solution presented in Yelda et al. (2010) to refine our astrometry. We adopt a pixel scale of 9.963 ± 0.005 mas pixel$^{-1}$ and a 0:13 ± 0:02 offset from north for the camera columns (Ghez et al. 2008). We did not apply any advanced LOCI processing to analyze the data.

Our observations are summarized in Table 1. Relative photometry was performed with IRAF’s apphot tasks using apertures that maximized the signal-to-noise of the companion. Generally, this was 1–1.4 times the FWHM of a point source. The apparent magnitude for the companion at $K$ is estimated by correcting the Two Micron All Sky Survey (2MASS) $Ks$ magnitude of 8.153 ± 0.023 for the primary as described by Wainscoat & Cowie (1992), namely, $K' - K = 0.22 (H - K)$, and using the relationship between $K$ and $Ks$ described by Carpenter (2001). HD 23514 then has a $K'$ magnitude of 8.13 ± 0.02, not too different from the $Ks$ magnitude. For the coronographic data, the primary is attenuated by a factor of 28.57 and 27.80 for the 600 and 800 mas diameter spots, respectively (R. Galicher, private communication). Multiple short exposures were obtained with integration times ranging from 10 to 60 s, as listed in Table 1, and the companion is clearly visible in most of the individual frames. The primary is saturated in the 2006, 2007, and 2008 $Ks$ and $K'$ long exposures. The individual frames were registered to shorter, unsaturated frames using IRAF’s register task. Photometry for these paired observations is performed with the same aperture size, but takes into account the different exposure times.

We measure the candidate companion at a separation of $2.645 \pm 0.002$ with P.A. 227:52 ± 0:02 in our 2010 coronographic observations. The object has remained at the same location between 2006 and 2010 (see Table 2 and Figure 1). Had this been a more distant background object, then, based on the primary’s proper and parallactic motion ($20.5 \pm 0.4 \text{ mas yr}^{-1}, -42.6 \pm 0.5 \text{ mas yr}^{-1}$; Zacharias et al. 2010), after

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6 IRAF is distributed by the National Optical Astronomy Observatory, which is operated by the Association of Universities for Research in Astronomy, Inc., under cooperative agreement with the National Science Foundation.
7 Written by S. Metchev, see http://www.astro.sunysb.edu/metchev/ao.html
5 years this object should have been separated by 2′60 ± 0′02 and had a P.A. of 232°7 ± 1°0 (see Figure 2). As will be mentioned in Section 3, the 2006 ADI data are somewhat unreliable as evidenced by the large uncertainties in Table 2. If we instead compare our astrometry starting from 2007, our result yields an expected position of a stationary background source of 2′61 ± 0′01 with P.A. of 230°78 ± 0′29. Over this shorter 4 year baseline, a background object can be ruled out at the ∼2σ level. The consistent values for separation and P.A. for the object from 2006 to 2010 imply that this is a companion to the system or is a nearby comoving Pleiades member, a possibility we address in Section 3.1.

The quoted photometry and astrometry in Table 2 are the averages over all frames. The uncertainties are standard deviations of multiple frames; for the apparent magnitude, this error is added in quadrature with the primary’s photometric error (∼0.02 mag). Aperture sizes were chosen to optimize the signal-to-noise of the secondary and correspond to roughly 1′′–1″ FWHM. The rotation of the field of view smeared out the companion (no advanced ADI/LOCI processing was used to analyze the data).

### Table 1

HD 23514 Observations

| UT Date    | Filter | Integration Time (s) | N
| --- | --- | --- | --- |
| 2006 Dec 10 | K' | 30 | 2 | 60 | 18 | ADI mode, primary saturated |
| 2006 Dec 10 | K' | 0.2 | 100 | 20 | 9 | ADI mode, secondary not detected |
| 2006 Dec 10 | K' | 0.005 | 50 | 0.25 | 12 | ADI mode, secondary not detected |
| 2007 Oct 25 | K' | 30 | 2 | 60 | 14 | Primary saturated |
| 2007 Oct 25 | K' | 0.018 | 20 | 0.36 | 8 | Secondary not detected |
| 2007 Oct 25 | K' | 0.005 | 50 | 0.25 | 6 | Secondary not detected |
| 2008 Nov 4 | Ks | 20 | 1 | 20 | 8 | Primary saturated |
| 2008 Nov 4 | Ks | 0.5 | 20 | 10 | 15 | Secondary detected in 9/15 frames |
| 2009 Nov 1 | H | 1 | 60 | 60 | 7 |
| 2009 Nov 2 | Ks C600 | 30 | 1 | 30 | 14 | Coronographic; 600 mas diameter spot |
| 2010 Oct 30 | J | 0.053 | 200 | 10.6 | 5 |
| 2010 Oct 30 | H | 0.053 | 200 | 10.6 | 10 |
| 2010 Oct 30 | Ks | 0.1 | 200 | 20 | 5 |
| 2010 Oct 30 | Ks C800 | 6 | 2 | 12 | 10 | Coronographic; 800 mas diameter spot |

**Notes.** All data were taken with the NIRC2 narrow camera at the 10 m Keck telescope. Data not labeled as ADI or coronographic were taken as dithered observations in P.A. mode. The short exposure frames where the secondary is not detected are used to register those in which the primary is saturated. Values quoted in Table 2 are averages over all frames.

### Table 2

HD 23514 Measurements

| UT Date    | Filter | Aperture Size (mas) | Δm (mag) | Apparent Mag (mag) | Separation (°) | P.A. (° E of N) |
| --- | --- | --- | --- | --- | --- | --- |
| 2006 Dec 10 | K' | 45 | 7.25 ± 0.42 | 15.38 ± 0.42 | 2.64 ± 0.02 | 228.7 ± 1.0 |
| 2007 Oct 25 | K' | 25 | 7.19 ± 0.34 | 15.32 ± 0.34 | 2.64 ± 0.01 | 227.8 ± 0.3 |
| 2008 Nov 4 | Ks | 20 | 6.66 ± 0.33 | 14.81 ± 0.33 | 2.62 ± 0.04 | 227.5 ± 0.5 |
| 2009 Nov 1 | H | 25 | 7.32 ± 0.08 | 15.61 ± 0.08 | 2.642 ± 0.003 | 227.51 ± 0.04 |
| 2009 Nov 2 | Ks C600 | 20 | 6.59 ± 0.22 | 14.74 ± 0.22 | 2.642 ± 0.001 | 227.54 ± 0.03 |
| 2010 Oct 30 | J | 25 | 7.44 ± 0.12 | 15.92 ± 0.12 | 2.644 ± 0.004 | 227.5 ± 0.1 |
| 2010 Oct 30 | H | 25 | 7.10 ± 0.05 | 15.39 ± 0.06 | 2.644 ± 0.002 | 227.48 ± 0.05 |
| 2010 Oct 30 | Ks | 25 | 6.70 ± 0.08 | 14.85 ± 0.08 | 2.642 ± 0.005 | 227.47 ± 0.09 |
| 2010 Oct 30 | Ks C800 | 25 | 6.90 ± 0.09 | 15.05 ± 0.09 | 2.645 ± 0.002 | 227.52 ± 0.02 |

**Notes.** All data were taken with the NIRC2 camera at the 10 m Keck telescope, as listed in Table 1. The uncertainties are standard deviations of multiple frames; for the apparent magnitude, this error is added in quadrature with the primary’s photometric error (∼0.02 mag). Aperture sizes were chosen to optimize the signal-to-noise of the secondary and correspond to roughly 1′′–1″ FWHM for a point source. In the ADI data (2006), a larger aperture size was used (∼2.4× FWHM) as the rotation of the field of view smeared out the companion (no advanced ADI/LOCI processing was used to analyze the data).

Evolutionary models for a 100 Myr-old F6 star like HD 23514 (1.35 M⊙ and Teff ~ 6400 K; Rhee et al. 2008) predict an absolute Ks magnitude of about 2.5 (Baraffe et al. 1998, 2002) giving a distance modulus of 5.65 and a distance of 135 pc. An additional distance estimate can be obtained by considering that this star is part of the Pleiades, which lies 135.5 pc away (An et al. 2007; Soderblom et al. 2005; see also Table 3 in van Leeuwen 2009). The Pleiades extends nearly 10° in diameter (van Leeuwen 2009 and references therein); if we assume a spherical distribution, this amounts to a possible radial extent of 11.7 pc. Hence, the distance to HD 23514 would be somewhere between 122 pc and 145 pc; we adopt a distance of 135 ± 10 pc. Considering our Ks photometry, the companion has ΔKs = 6.77 ± 0.18 (see fourth column in Table 2), which, when compared with the being late-M (~M7–9; see Kirkpatrick & McCarthy 1994). The J – H color is somewhat discrepant being bluer than expected; however, as shown in Figure 3, the measurement is consistent given the uncertainties.

### 3. RESULTS

The quoted photometry and astrometry in Table 2 are the averages of all the frames and the uncertainties are standard deviations of the individual measurements. The more precise astrometry present in the latter epochs is possible since both the primary and secondary are detected and are unsaturated in the same frame. A companion 6.8 mag fainter than the primary F6 star at Ks would be a late-M dwarf (see Section 3). The J − Ks and H − Ks colors of this object are also consistent with...
2MASS photometry for HD 23514, gives an apparent magnitude of $K_s = 14.92 \pm 0.18$. For our adopted distance, the absolute $K_s$ magnitude of the companion is $9.27 \pm 0.24$.

To estimate the mass of the companion we make use of low-mass/substellar evolutionary models. The DUSTY evolutionary models of Chabrier & Baraffe (2000) take into account the formation of condensates in the atmosphere and are appropriate for low-temperature objects down to $\sim 1300$ K. With these models, a 100 Myr object with absolute $K$ magnitude 9.27 would have a mass somewhere between 0.06 and 0.07 solar masses and an effective temperature of $\sim 2700$ K. The evolutionary models of Baraffe et al. (1998) use the NextGen dust-free atmospheres and are appropriate for objects with $T_{\text{eff}} \geq 2300$ K. These models similarly predict $T \sim 2600$ K and mass $\sim 0.05$–$0.06$ solar masses when compared to the $K_s$-band photometry. The $J$- and $H$-band photometry suggest somewhat lower masses (down to 0.05 solar masses) and cooler temperatures ($\sim 2500$ K). Combining all results together, we can infer that the companion has a mass of $0.06 \pm 0.01$ solar masses. This is below the stellar/substellar boundary making the object a brown dwarf.

The temperature, likewise, appears to be $2600 \pm 100$ K, placing it at spectral type $\sim$ M7 (see Figure 2 in Reyle et al. 2011), consistent with the near-infrared colors (Kirkpatrick & McCarthy 1994).

No other object is detected in the $10'' \times 10''$ field of view. At the distance to HD 23514, this amounts to a radius of 675 AU. Figure 4 presents the $5\sigma$ magnitude limit as a function of distance from the primary for the two coronographic $K_s$ observations (2009 and 2010). These are our best limits for HD 23514. Limits are obtained by performing aperture photometry over blank regions of the sky at annuli surrounding the primary. These limits are averaged over the multiple frames.
No companion is detected with a limit of $\sim 11–12$ mag beyond 1.5′ ($\sim$200 AU). This suggests an absolute magnitude limit of $\sim 14$ at $K_s$, or a mass of nearly $\sim 11$ Jupiter masses when compared to evolutionary models (Chabrier & Baraffe 2000; Baraffe et al. 2003).

The average $K_s$ magnitude for the secondary, 14.92, differs from the $K'$ magnitude, 15.40, by half a magnitude. A late-M star is expected to have $H - K_s \approx 0.5$, which suggests $K' - K_s \approx 0.1$, not enough to account the difference. However, the uncertainty in our $K'$ photometry is the highest of our measurements, at nearly 0.4 mag. For the 2006 data, the uncertainty is a result of the larger aperture size ($\sim 2.4 \times$ FWHM) needed as the M-type companion is smeared out in the ADI exposures. For 2007 and 2008, the primary is saturated and the secondary’s flux (and location) is compared to separate, shorter exposures as described in Section 2. The high uncertainty, combined with the expected difference in the $K'$ and $K_s$ filters, is enough to account for the discrepancy.

### 3.1. Is HD 23514B a Free-floating Pleiad?

While the common motion with HD 23514A is suggestive, there exists the possibility that the observed object may be a more distant (or closer) free-floating Pleiades brown dwarf. As a member of the Pleiades, it would have about the same proper motion and thus appear to be comoving with HD 23514. The most robust way to ascertain this would be to observe the system over many years in order to detect (or rule out) orbital motion. However, statistical arguments suggest that the brown dwarf is indeed bound to HD 23514.

Jameson et al. (2002) used a group of surveys to estimate the spatial distribution of brown dwarfs in the Pleiades. HD 23514 is located about 1.7′ from the center (03h47m, +24°07′; Pinfield et al. 1998). At that distance, Jameson et al. (2002) suggest a brown dwarf (mass $\geq 0.05 M_\odot$) density of 2.7 deg$^{-2}$. However, more recent studies performed by Lodieu et al. (2007) and Moraux et al. (2003) suggest average brown dwarf (mass $\geq 0.03 M_\odot$) densities of 7.8 and 6.3 deg$^{-2}$, respectively. Moraux et al. (2003) surveyed the Pleiades in fields located 0′75–3.5′ away from the field center, Lodieu et al. (2007) incorporated that survey and in addition also covered the center of the Pleiades with UKIDSS. Thus, the area covered by these deeper surveys is similar in radial extent to that in Jameson et al. (2002; out to 2.2′ from the center), but the density of brown dwarfs is larger by a factor of about two than the average brown dwarf density of 4.2 deg$^{-2}$ found by Jameson et al. (2002). To account for these deeper surveys (mass $\geq 0.03 M_\odot$), we scale the density provided by Jameson et al. (2002) and find that, at HD 23514’s distance from the center of the Pleiades, the density of brown dwarfs is about $5 \pm 2$ deg$^{-2}$.

The likelihood of finding a free-floating Pleiades brown dwarf with mass $\geq 0.03 M_\odot$ in the field of view is thus about $4 \times 10^{-5}$.

The small likelihood derived lends weight to the idea that this is a bound companion. There are few brown dwarf companions known to stellar primaries (the well-known “brown dwarf desert” phenomenon; McCarthy & Zuckerman 2004; Metchev & Hillenbrand 2009). Even though the frequency of brown dwarf companions at separations $\gtrsim$30 AU is small—estimated to range from 0.5% to nearly 20% (see discussion in Kraus et al. 2008)—HD 23514B is more likely to be a bound companion than an isolated Pleiades brown dwarf.

If we assume that the orbit is circular and face-on, we can use the measured projected separation to estimate the yearly orbital motion of the system. Given a mass of $1.35 M_\odot$, we estimate a period of $\sim$6000 years. This yields an angular motion of $0.06$ year$^{-1}$ or a linear motion of $\sim 2.8$ mas year$^{-1}$. This is comparable to our astrometric precision in our later epochs (see Table 2), suggesting that a baseline of at least 5 more years would be needed to confirm orbital motion if one starts to see the curvature of the orbit. However, the yearly motion is likely to be smaller as the orbit may be inclined and/or eccentric.

It is instructive to consider whether or not a substellar object at that separation will remain bound over the 100 Myr lifetime of the Pleiades. Figure 5 presents the binding energy of resolved stellar and substellar binaries in the Pleiades (from Bouvier et al. 1997; Bouy et al. 2006). Note that since inclination and eccentricity are typically not available for these systems (and certainly not for HD 23514), the true binding energy may be somewhat different than that plotted here. Despite not being the most widely separated binary in the Pleiades (Bouvier et al. present systems at $\sim 900$ AU), HD 23514 does have the lowest binding energy among the stellar mass binaries. However, substellar Pleiades binaries with separations $\leq 20$ AU have comparable or lower binding energies. The similar binding energies suggest that stellar interactions within the Pleiades, while more frequent than in the field, may not be enough to disrupt the HD 23514 system in timescales much shorter than 100 Myr. We note that HIP 78530 (Lafrenière et al. 2011) and IRXS J160929.1–210524 (Lafrenière et al. 2010, 2008) both host substellar companions at wide separations in the 11 Myr-old Upper Scorpius region (Pecault et al. 2012). These are considered physically bound based on common proper motion, similar to the case of HD 23514. Both systems have estimated binding energies lower than that of HD 23514.

### 4. DISCUSSION

Previous searches for brown dwarf companions in the Pleiades have focused on low-mass stars or free-floating brown dwarfs (e.g., Stauffer et al. 2007; Lodieu et al. 2007; Bouy et al. 2006; Martín et al. 2003; Pinfield et al. 2000). Bouvier et al. (1997) used adaptive optics to observe 144 G- and K-type stars in the Pleiades. The lowest mass companion they found was $0.15 M_\odot$, although they were sensitive to objects with masses down to $\sim 0.03 M_\odot$ at separations of $\sim 1′$. A deeper study conducted by Metchev & Hillenbrand (2009) also looked...
at solar-type stars, but found no substellar companions among \(\sim 20\) Pleiades stars. Hence, while there may be hundreds of free-floating brown dwarfs in the Pleiades (Lodieu et al. 2007; Jameson et al. 2002), this is among the first brown dwarfs detected as a companion to a Sun-like star. The scarcity of companion brown dwarfs to the \(\sim 300\) solar-type stars in the Pleiades (Staufter et al. 2007; Pinfield et al. 1998) is consistent with the findings of a brown dwarf desert among solar-type stars out to separations of \(\sim 1000\) AU (McCarthy & Zuckerman 2004; Metchev & Hillenbrand 2009).

HD 23514 is surrounded by a substantial amount of warm (\(\sim 700\) K) dust in a thin ring located \(\sim 0.25\) AU from the star if the emission comes from large blackbody grains or at most a few AU if the grains are smaller and radiate less efficiently (Rhee et al. 2008). At a distance of 135 pc, the companion in Figure 1 has a projected separation of about 360 AU, far larger than the dust semimajor axis. Only a handful of systems are known to contain substantial quantities (\(L_{\text{IR}}/L_\star \gtrsim 0.1\%\)) of warm dust: Cha-Near member EF Cha (Rhee et al. 2007), \(\beta\) Pic member HD 172555 (Lisse et al. 2009), Lower Centaurus Crux member HD 113766 (Chen et al. 2006), AB Dor member HD 15407 (Melis et al. 2010), M47 member P1121 (Gorlova et al. 2004), and NGC2547 member ID8 (Gorlova et al. 2007).

BD+20 307 is another main-sequence star known to contain a large amount of warm dust (Song et al. 2005); however, it is much older (\(\sim 1\) Gyr) than these other systems (Zuckerman et al. 2008; Weinberger 2008). Of these eight systems, HD 23514, HD 15407, HD 172555, BD+20 307, and HD 113766 are known to be binary or triple systems. All are wide separation systems (>100 AU) with the exception of BD+20 307, whose separation is only about 0.05 AU (though with a high probability of a third more distant, and as yet unseen, object; see Tokovinin et al. 2006). Interestingly, HD 23514, HD 15407, and HD 172555 all exhibit signs of silica emission, suggesting that high-velocity impacts produced the dust in the system (Melis et al. 2010; Lisse et al. 2009).

Binaries with separations of a few tens of AU are less likely to contain substantial amounts of dust when compared with single stars or with wide separation binaries (Trilling et al. 2007; Rodríguez & Zuckerman 2012). However, if HD 23514 hosts a tertiary companion, say a close-in planet, whose initial inclination is different than that of the substellar companion, the Kozai mechanism (Kozai 1962) can work to disrupt its orbit by continuously changing the inclination and eccentricity. This can potentially stir up planetesimals in the system and thus enhance collisions in the terrestrial zone (for example, see Malmborg et al. 2007; Innanen et al. 1997). Rhee et al. (2008) suggest a catastrophic or even planet–planet collision to account for the large amount of dust in the system. Such an event could take place if the eccentricity of a planet or large planetesimal is sufficiently increased through the Kozai mechanism. A large eccentricity can lead to high-velocity impacts near periastron, which can account for the silica emission observed in the system. Equation (36) in Ford et al. (2000) can be used to estimate the period of the eccentricity oscillation of this tertiary body. As an illustrative example, if we consider a planet or planetesimal at 5 AU, and assume that HD 23514B’s orbit is circular and its projected separation is the semimajor axis, the period of eccentricity oscillations is \(\sim 80\) Myr. Planets on closer orbits would have longer oscillation periods, for example, \(\sim 110\) Myr for a planet at 3 AU. While there are many unknowns, it is interesting to note that these periods are comparable to the age of the system. Further monitoring of the system, as well as deeper searches for any additional companions closer to the star, will be key in determining the relationship, if any, between the secondary companion and the dust around the primary.

5. CONCLUSIONS

Using adaptive optics imaging at Keck, we have discovered a substellar companion to the dusty Pleiades star HD 23514. Based on comparison with evolutionary models, we estimate the companion to have a mass of about \(0.06 \pm 0.01\ M_\odot\) and a temperature of \(2600 \pm 100\ K\). HD 23514B and HII 1348B are the first brown dwarfs detected as companions to Sun-like Pleiads.

HD 23514 is one of the dustiest main-sequence stars known to date with \(L_{\text{IR}}/L_\star \sim 2\%\). The warm dust present in the system is located within a few AU of the primary. In contrast, the companion has a projected separation of \(\sim 360\) AU. At that distance, the companion’s gravity is expected to have little influence over the evolution of the warm dust seen around the primary. However, if a tertiary object were present in the system very close to the star, the Kozai mechanism can affect its orbit and possibly enhance collisions that generate dust.

We thank J. Staufter for useful discussions on the Pleiades, R. Galicher for the NIRC2 coronographic attenuation, and S. Yelda for assistance in NIRC2 reduction. We thank our anonymous referee for a prompt review and constructive suggestions. The data presented herein were obtained at the W. M. Keck Observatory, which is operated as a scientific partnership among the California Institute of Technology, the University of California, and the National Aeronautics and Space Administration. The Observatory was made possible by the generous financial support of the W. M. Keck Foundation. The authors wish to recognize and acknowledge the very significant cultural role and reverence that the summit of Mauna Kea has always had within the indigenous Hawaiian community. We are most fortunate to have the opportunity to conduct observations from this mountain. This research was supported in part by NASA grants to UCLA. Portions of this work were performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344. D.R.R. acknowledges support from project BASAL PB-06 de CONICYT and a Joint Committee ESO-Government of Chile grant.

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