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SDSS J042348.57−041403.5AB: A BROWN DWARF BINARY STRADDLING THE L/T TRANSITION

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ABSTRACT

We present the discovery of SDSS J042348.57−041403.5 as a closely separated (0″.16) brown dwarf binary, resolved by the *Hubble Space Telescope* Near-Infrared Camera and Multi-Object Spectrometer. Physical association is deduced from the angular proximity of the components and constraints on their common proper motion. SDSS 0423−0414AB appears to be composed of two brown dwarfs with spectral types L6 ± 1 and T2 ± 1. Hence, this system straddles the transition between L dwarfs and T dwarfs, a unique evolutionary phase of brown dwarfs characterized by substantial shifts in spectral morphology over an apparently narrow effective temperature range. Binarity explains a number of unusual properties of SDSS 0423−0414, including its overluminosity and high effective temperature compared to other early-type T dwarfs, and possibly its conflicting spectral classifications (L7.5 in the optical, T0 in the near-infrared). The relatively short estimated orbital period of this system (∼15–20 yr) and the presence of Li I absorption in its combined light spectrum make it an ideal target for both resolved spectroscopy and dynamical mass measurements. SDSS 0423−0414AB joins a growing list of late-L/early-T dwarf binaries, the high percentage of which (∼50%) may provide a natural explanation for observed peculiarities across the L/T transition.

Subject headings: binaries: visual — stars: fundamental parameters — stars: individual (SDSS J042348.57−041403.5) — stars: low-mass, brown dwarfs

Online material: color figures

1. INTRODUCTION

The atmospheres of the lowest luminosity brown dwarfs, hosting abundant molecular gas species and liquid and solid condensates, have more in common with the atmospheres of giant planets than main-sequence stars. Their unique spectral morphologies have brought about the introduction of two new spectral classes, L dwarfs and T dwarfs (Kirkpatrick 2005 and references therein). The former, more luminous objects have red near-infrared (NIR) colors resulting from warm photospheric condensate dust clouds; the latter have blue NIR colors and relatively dust-free photospheres (e.g., Tsuji et al. 1996; Chabrier et al. 2000). The transition between these two classes has turned out to be rather intriguing. Despite significant evolution in spectral morphology, effective temperatures ($T_{\rm eff}$) appear to be largely invariant between late-type L dwarfs and mid-type T dwarfs (Golimowski et al. 2004), while surface fluxes at 1 μm actually increase (e.g., Dahn et al. 2002; Tinney et al. 2003). It has been surmised that the L/T transition may be modulated by a rapid evolution of photospheric condensate dust clouds, as opposed to the gradual sinking of these clouds as predicted by atmospheric models (e.g., Ackerman & Marley 2001). Burgasser et al. (2002a) have proposed that these clouds break apart, creating bright regions analogous to Jupiter's 5 μm hot spots (Westphal et al. 1974). Knapp et al. (2004) postulate a phase of "rapid rainout." Tsuji & Nakajima (2003), however, argue that the 1 μm brightening arises from variations in secondary parameters, such as age or metallicity. With such diversity in its interpretation, the L/T transition remains an outstanding problem in brown dwarf astrophysics.

One key source in the midst of this transition is SDSS J042348.57−041403.5 (hereafter SDSS 0423−0414). Identified by Geballe et al. (2002) in the Sloan Digital Sky Survey (York et al. 2000), this relatively bright brown dwarf exhibits weak CH_4 absorption at 1.6 and 2.2 μm and red NIR colors indicative of residual photospheric condensate dust. While these properties are consistent with those of other early-type T dwarfs, SDSS 0423−0414 is noteworthy as its optical spectrum indicates an earlier L7.5 classification (Cruz et al. 2003), and it is ∼1 mag brighter in the NIR than other similarly typed dwarfs (Vrba et al. 2004). SDSS 0423−0414 is also one of the few brown dwarfs to exhibit both 6708 Å Li I absorption and 6563 Å Hα emission (Burgasser et al. 2003a). It has been surmised that this source could be a young, extremely low mass brown dwarf; a distended rapid rotator; or an unresolved binary. In this Letter, we demonstrate that SDSS 0423−0414 is a binary system straddling the L/T transition.

2. OBSERVATIONS

SDSS 0423−0414 was observed as part of *Hubble Space Telescope* (*HST*) general observer program 9833, targeting 22 T dwarfs spanning spectral types T0 to T8 with the Near-Infrared Camera and Multi-Object Spectrometer (NICMOS). Sources were observed with the NIC1 detector (pixel scale 0″.0432) and the F110W and F170M filters, the former sampling the spectral flux peak of T dwarfs and the latter sampling the 1.6 μm CH_4 band. F110W − F170M color measures the depth of this band, distinguishing T dwarfs from other objects and providing an estimate of their spectral type. Full details of our *HST* program will be presented in a forthcoming publication (A. J. Burgasser et al. 2005, in preparation).

Observations of SDSS 0423−0414 were made on 2004 July

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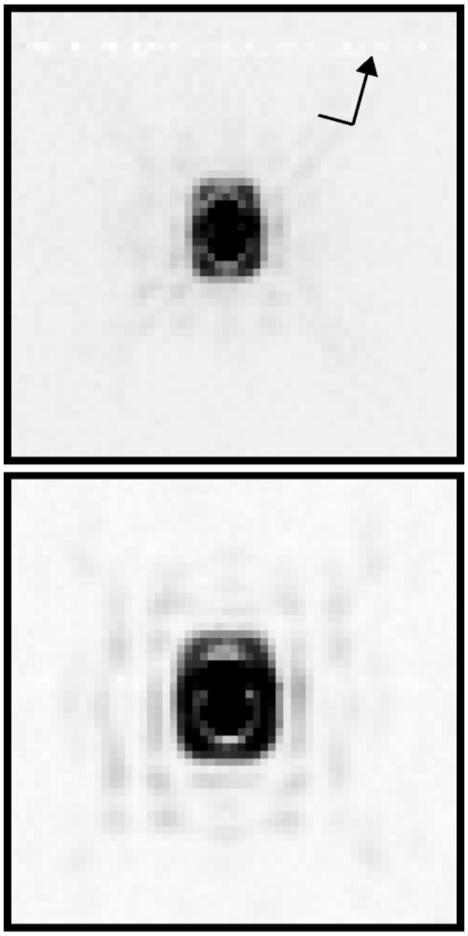

FIG. 1.—*HST* NICMOS F110W (*top*) and F170M (*bottom*) observations of the binary SDSS 0423−0414AB. Images are 2ʺ.5 on a side, and orientation is given by the compass in the top panel indicating north (*arrow*) and east. [*See the electronic edition of the Journal for a color version of this figure.*]

22 (UT). Multiple exposures totaling 407.7 and 1519.2 s were obtained in the F110W and F170M filters, respectively, dithering in a spiral pattern with 1ʺ.3 (30 NICMOS pixels) offsets. All data were reduced using the STScI calibration pipeline with CALNICA and the most recent calibration files as of 2005 August. Combined mosaic images were also acquired from the CALNICB output of the STScI pipeline.

Figure 1 displays 2ʺ.5 × 2ʺ.5 subsections of the mosaic images centered on SDSS 0423−0414. Two overlapping point sources are resolved, extending along a north-south axis. Aperture photometry for the combined pair was measured using the IRAF[7] APPHOT routine, employing a wide (20 pixel radius) circular aperture containing $\gtrsim$99% of the total flux of the pair. Instrumental magnitudes were corrected to the Arizona Vega system using NICMOS flux calibration parameters; Vega fluxes of 1785.9 and 946.2 Jy for F110W and F170M, respectively (Mobasher & Roye 2004); and zero points of 0.02 mag. Uncertainties in the photometry include photon shot noise and read noise, 0.2% uncertainty in the NICMOS photometric calibration, 1% stability in the zero point, and 2% uncertainty due to the extreme spectral morphology of the target (Mobasher & Roye 2004). Derived magnitudes are listed in Table 1.

TABLE 1
PROPERTIES OF SDSS J042348.57−041403.5AB

Parameter	Value	Reference
Spectral type	L7.5/T0[a]	1, 2
A	L6 ± 1	3
B	T2 ± 1	3
Distance	15.2 ± 0.4 pc	4
μ	0ʺ.333 ± 0ʺ.003 yr^{-1}	4
θ	284°.2 ± 0°.2	4
$\log(L_{bol}/L_{\odot})$	−4.14 ± 0.04[b]	5
A	−4.39 ± 0.09	3
B	−4.50 ± 0.10	3
T_{eff}	1450–1825 K[b]	5
A	1250–1575 K	3
B	1200–1500 K	3
F110W	15.27 ± 0.03 mag[b]	3
F170M	13.58 ± 0.03 mag[b]	3
ΔF110W	0.58 ± 0.11 mag	3
ΔF170M	0.85 ± 0.11 mag	3
ρ	0ʺ.1642 ± 0ʺ.0017	3
	2.45 ± 0.07 AU	3
ϕ	20°.3 ± 0°.8	3
M_{total}	0.08–0.14	3, 6
M_B/M_A	0.8–1.0	3
Period	∼15–20 yr	3

[a] Optical/NIR spectral type for combined light spectrum.
[b] For combined pair.
REFERENCES.—(1) Cruz et al. 2003; (2) Geballe et al. 2002; (3) this paper; (4) Vrba et al. 2004; (5) Golimowski et al. 2004; (6) Burrows et al. 1997.

To measure the component fluxes, we employed an iterative PSF fitting routine as described in Burgasser et al. (2003b). Model images were generated from PSFs of the unresolved sources 2MASS J05591914−1404488 and SDSS J125453.90−012247.4 (Burgasser et al. 2000; Leggett et al. 2000; also observed in our *HST* program) and compared to individual calibrated images of SDSS 0423−0414. A total of 78 fits were made at F110W and 50 fits at F170M. Table 1 lists the means and standard deviations of the angular separation (ρ), position angle (ϕ), and relative fluxes for the two sources. The southern source is brighter by 0.58 ± 0.11 and 0.85 ± 0.11 mag at F110W and F170M, respectively, while the measured separation (ρ = 0ʺ.1642 ± 0ʺ.0017) corresponds to a projected separation of 2.45 ± 0.07 AU at the distance of SDSS 0423−0414 (15.2 ± 0.4 pc; Vrba et al. 2004).

3. ANALYSIS

The colors of the two sources are each consistent with weak or absent 1.6 μm CH_4 absorption, as expected for a late-type L or early-type T dwarf. These colors are also consistent with earlier type stars, spectral types K–M. However, the latter are substantially brighter at optical wavelengths than L or T dwarfs, which have $R - J \gtrsim 6$ (Kirkpatrick et al. 1999). The absence of an optical counterpart at the position of SDSS 0423−0414 in SERC[8] ER survey images (R_{limit} ∼ 21–22) implies $R - J \gtrsim$ 5–6 and spectral types $\gtrsim$M6 for both components. In addition, no optical counterpart was detected in deep *R*- and *I*-band images obtained on 2003 January 24 (UT) using the Palomar

[7] 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.

[8] Sky Atlas and its Equatorial Extension (SERC) images were obtained from the Digitized Sky Survey image server maintained by the Canadian Astronomy Data Centre, which is operated by the Herzberg Institute of Astrophysics, National Research Council of Canada.

1.5 m Telescope facility CCD camera, down to $R \sim 22$ and $I \sim 20$. We therefore conclude that the two sources are L and/or T dwarfs.

Are they physically associated? Current estimates of the surface density of L and T dwarfs for $J \lesssim 16$ (consistent with the brightness of the secondary) are of order 10^{-3} deg^{-2} (Burgasser et al. 2002b; Cruz et al. 2003). Hence, the probability of two such objects lying within 1″ of each other is 8×10^{-5}, ruling out random alignment at the 99.98% confidence level. Common proper motion can be constrained by the fact that the pair is unresolved in Two Micron All Sky Survey (2MASS; Cutri et al. 2003) images, for which point sources can be resolved for separations $\gtrsim$1.″5 (Burgasser et al. 2005b). This restricts the motion of an unassociated source to 0.″08–0.″42 yr^{-1} at a position angle consistent within $\pm 40°$. These limits, coupled with the late spectrophotometric types and angular proximity of the two sources, lead us to conclude that they are physically associated.

The colors of the sources provide only rough constraints on their spectral types, L5–T3. Absolute magnitudes also provide weak constraints due to the inflections in absolute magnitude/spectral type trends around type T0. The $M_{\rm F110W}$ and $M_{\rm F170M}$ magnitudes of the brighter (A) component, 14.86 ± 0.12 and 13.08 ± 0.12, are consistent with both mid- and late-L (L5–L7) and early- and mid-T (T2–T4) types (A. J. Burgasser et al. 2005, in preparation). The absolute magnitudes of the fainter (B) component, 15.44 ± 0.12 and 13.93 ± 0.12, are similar to both early- (T0–T1) and mid-type (T4–T5) T dwarfs. To derive more precise estimates, we compared "hybrid" NIR spectra of late-type L and T dwarf components to the unresolved spectrum of SDSS 0423−0414 (Geballe et al. 2002; cf. Cruz et al. 2004). Various combinations of low-resolution NIR spectra (Leggett et al. 2000; Geballe et al. 2002; Knapp et al. 2004) for 2MASS J15074769−1627386 (L5.5[9]), SDSS J023617.93+004855.0 (L6.5), Gliese 584C (L8), SDSS J015141.69+124429.6 (T1), SDSS J125453.90−012247.4 (T2), and SDSS J175032.96+175903.9 (T3.5) were made after scaling the spectra to match the component *HST* fluxes. Figure 2 demonstrates how an L6.5+T2 combination provides an excellent match to the spectral energy distribution of SDSS 0423−0414, particularly CH_4 and H_2O band strengths. The hybrid spectrum has F110W − F170M = 1.66, similar to the measured color of 1.69 ± 0.04. Good agreements were also found with L5.5+T1, L5.5+T2, and L6.5+T1 combinations. Using an L8 primary resulted in CH_4 bands that were too weak and excessive *K*-band flux, while a T3.5 secondary gave CH_4 bands that were too strong. Combining these results with comparisons of the individual colors and absolute magnitudes, we estimate spectral types of L6 ± 1 and T2 ± 1 for the two components of SDSS 0423−0414, although resolved spectroscopy is required to verify and improve the accuracy of these classifications.

The binary nature of SDSS 0423−0414AB explains many of its unusual properties, most notably its overluminosity and high $T_{\rm eff}$ relative to similarly classified brown dwarfs. Golimowski et al. (2004) derive $T_{\rm AB}$ = 1450–1825 K from the combined luminosity, ~300 K hotter than typical L8–T2 brown dwarfs. The component temperatures ($T_{\rm A}$, $T_{\rm B}$) can be deduced from the relative luminosities and Stefan's law, assuming similar radii. However, the luminosity ratio is difficult to estimate for this system due to the inflection in absolute brightnesses across the L/T transition. If $M_{\rm F110W} \propto L$, then $L_{\rm B}/L_{\rm A} \approx 0.6$; however, both components could have identical luminosities. Assuming an average $L_{\rm B}/L_{\rm A} \approx 0.8$, we estimate $T_{\rm A}$ = 1250–1575 K and $T_{\rm B}$ = 1200–1500 K, consistent with most $T_{\rm eff}$/spectral type trends to date (e.g., Golimowski et al. 2004; Nakajima et al. 2004; Vrba et al. 2004). We estimate the mass ratio of this pair to be $M_{\rm B}/M_{\rm A} \approx (L_{\rm B}/L_{\rm A})^{0.38}$ = 0.8–1.0 (Burrows et al. 2001). The combination of close separation and near-unity mass ratio are common among substellar field binaries (e.g., Bouy et al. 2003; Close et al. 2003).

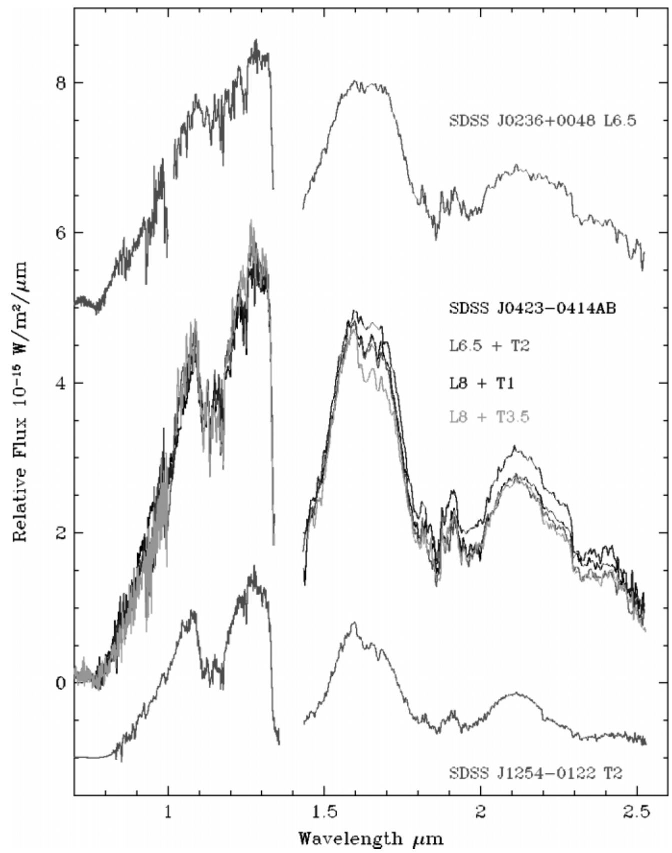

FIG. 2.—Comparison of red optical and NIR spectral data for SDSS 0423−0414 (*middle*; in black) to various pairings of late-type L and T dwarf spectra. The best match of a combined L6.5 (*top*) and T2 (*bottom*) is shown overlaid on the spectrum of SDSS 0423−0414. In contrast, later type primaries (e.g., L8+T1) and secondaries (L8+T3.5) yield poor agreement in band strengths and/or $H - K$ color. Earlier type primaries and later type secondaries fail to reproduce the absolute magnitudes of the components. [*See the electronic edition of the Journal for a color version of this figure.*]

4. DISCUSSION

SDSS 0423−0414 joins a growing list of visually resolved substellar binaries, of which roughly 30 are now known (e.g., Siegler et al. 2005). More intriguing is the addition of another L/T transition binary. Seven binaries with combined light spectral types spanning L7–T2 have been identified, including DENIS J020529.0−115925, 2MASS J17281150+3948593, 2MASS J21011544+1756586, DENIS J225210.73−173013.4, Gliese 337CD, 2MASS J05185995−2828372 (Bouy et al. 2003; Gizis et al. 2003; Cruz et al. 2004; Burgasser et al. 2005b; Reid et al. 2005), and now SDSS 0423−0414. This is out of the 15 L7–T2 dwarfs so far imaged at high resolution with *HST* (Reid et al. 2001, 2005; Bouy et al. 2003; Gizis et al.

[9] Spectral types given here are based on the NIR classification schemes of Geballe et al. (2002) and Burgasser et al. (2005a).

2003; A. J. Burgasser et al. 2005 and K. L. Cruz et al. 2005, both in preparation), implying a binary fraction of 47^{+13}_{-12}%. Even considering biases incurred from the sources having been chosen from magnitude-limited search samples, this fraction is still over twice that of magnitude-limited samples of early-type L dwarfs and mid- and late-type T dwarfs (∼20%; Reid et al. 2001; Gizis et al. 2003; Burgasser et al. 2003b), and represents a lower limit due to the probable existence of tighter, unresolved systems. An excess of late-L/early-T binaries could provide a natural explanation for many of the photometric and spectroscopic peculiarities observed across the L/T transition. A more rigorous analysis of binary fraction trends and their implications will be presented in a forthcoming publication.

The close separation and proximity of the SDSS 0423−0414 pair makes it a useful system for dynamical mass measurements. Assuming an age of 1–5 Gyr for this system (typical for field sources) and component $T_{\rm eff}$ values as deduced above, evolutionary models (Burrows et al. 1997) predict component masses of 0.040–0.075 $M_{\odot}$; at least one component has $M \lesssim 0.065\ M_{\odot}$ due to the presence of Li I absorption in the composite optical spectrum. These estimates imply an orbital period of 15–20 yr (assuming an orbital separation of 1.26ρ; Fischer & Marcy 1992). Hence, *HST* and/or ground-based adaptive optics observations should be able to measure significant orbital motion over the next few years. Furthermore, Liu & Leggett (2005) have pointed out that binary systems with Li absorption can be age-dated to higher precision than other field brown dwarfs, particularly if only one component exhibits the Li I line. This system could therefore be exploited to empirically test brown dwarf theoretical models with precise mass and age measurements. Resolved spectroscopy and monitoring observations are needed to more fully characterize the component brown dwarfs, but such observations will provide crucial empirical constraints on their physical properties and the underlying physics of the L/T transition.

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REFERENCES

Ackerman, A. S., & Marley, M. S. 2001, ApJ, 556, 872
Bouy, H., Brandner, W., Martín, E. L., Delfosse, X., Allard, F., & Basri, G. 2003, AJ, 126, 1526
Burgasser, A. J., Geballe, T. R., Leggett, S. K., Kirkpatrick, J. D., & Golimowski, D. A. 2005a, ApJ, submitted
Burgasser, A. J., Kirkpatrick, J. D., Liebert, J., & Burrows, A. 2003a, ApJ, 594, 510
Burgasser, A. J., Kirkpatrick, J. D., & Lowrance, P. J. 2005b, AJ, 129, 2849
Burgasser, A. J., Kirkpatrick, J. D., Reid, I. N., Brown, M. E., Miskey, C. L., & Gizis, J. E. 2003b, ApJ, 586, 512
Burgasser, A. J., Marley, M. S., Ackerman, A. S., Saumon, D., Lodders, K., Dahn, C. C., Harris, H. C., & Kirkpatrick, J. D. 2002a, ApJ, 571, L151
Burgasser, A. J., et al. 2000, AJ, 120, 1100
———. 2002b, ApJ, 564, 421
Burrows, A., Hubbard, W. B., Lunine, J. I., & Liebert, J. 2001, Rev. Mod. Phys., 73, 719
Burrows, A., et al. 1997, ApJ, 491, 856
Chabrier, G., Baraffe, I., Allard, F., & Hauschildt, P. 2000, ApJ, 542, 464
Close, L. M., Siegler, N., Freed, M., & Biller, B. 2003, ApJ, 587, 407
Cruz, K. L., Burgasser, A. J., Reid, I. N., & Liebert, J. 2004, ApJ, 604, L61
Cruz, K. L., Reid, I. N., Liebert, J., Kirkpatrick, J. D., & Lowrance, P. J. 2003, AJ, 126, 2421
Cutri, R. M., et al. 2003, Explanatory Supplement to the 2MASS All Sky Data Release (Pasadena: IPAC)
Dahn, C. C., et al. 2002, AJ, 124, 1170
Fischer, D. A., & Marcy, G. W. 1992, ApJ, 396, 178
Geballe, T. R., et al. 2002, ApJ, 564, 466
Gizis, J. E., Reid, I. N., Knapp, G. R., Liebert, J., Kirkpatrick, J. D., Koerner, D. W., & Burgasser, A. J. 2003, AJ, 125, 3302
Golimowski, D. A., et al. 2004, AJ, 127, 3516
Kirkpatrick, J. D. 2005, ARA&A, 43, 195
Kirkpatrick, J. D., et al. 1999, ApJ, 519, 802
Knapp, G., et al. 2004, AJ, 127, 3553
Leggett, S. K., et al. 2000, ApJ, 536, L35
Liu, M. C., & Leggett, S. K. 2005, ApJ, 634, 616
Mobasher, B., & Roye, E. 2004, *HST* Data Handbook for NICMOS, Version 6.0 (Baltimore: STScI)
Nakajima, T., Tsuji, T., & Yanagisawa, K. 2004, ApJ, 607, 499
Reid, I. N., Gizis, J. E., Kirkpatrick, J. D., & Koerner, D. 2001, AJ, 121, 489
Reid, I. N., Lewitus, E., Cruz, K. L., & Burgasser, A. J. 2005, ApJ, submitted
Siegler, N., Close, L. M., Cruz, K. L., Martín, E. L., & Reid, I. N. 2005, ApJ, 621, 1023
Tinney, C. G., Burgasser, A. J., & Kirkpatrick, J. D. 2003, AJ, 126, 975
Tsuji, T., & Nakajima, T. 2003, ApJ, 585, L151
Tsuji, T., Ohnaka, K., Aoki, W., & Nakajima, T. 1996, A&A, 308, L29
Vrba, F. J., et al. 2004, AJ, 127, 2948
Westphal, J. A., Matthews, K., & Terrile, R. J. 1974, ApJ, 188, L111
York, D. G., et al. 2000, AJ, 120, 1579