

DISCOVERY OF THE WIDEST VERY LOW MASS FIELD BINARY

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ABSTRACT

We present the discovery of the widest (~ 6700 AU) very low mass (VLM) field binary to date, found in a proper motion cross-match of the Sloan Digital Sky Survey and the Two Micron All Sky Survey. Our follow-up J -band imaging provides a 10 year baseline for measuring proper motions. Consequently, we are able to confirm the common proper motion of the pair to within 10 mas, implying a 99.5% probability of their physical association. Near-infrared spectra of the components indicate spectral types of $M6 \pm 1$ and $M7 \pm 1$. The system resides at a spectroscopic distance of 105 ± 13 pc and has an angular separation of $63''.38 \pm 0''.05$. We have used evolutionary models to infer component masses of $0.105^{+0.029}_{-0.017} M_{\odot}$ and $0.091^{+0.010}_{-0.007} M_{\odot}$. The large separation and low binding energy of this system can provide constraints for formation models of VLM stars.

Key words: binaries: general – stars: formation – stars: individual (2MASS J12583501+4013083, 2MASS J12583798+4014017) – stars: low-mass, brown dwarf

Online-only material: color figure

1. INTRODUCTION

Studies of the low end of the stellar initial mass function have made great strides in recent years, and have revealed a large population of very low mass (VLM; $M \lesssim 0.1 M_{\odot}$) stars and brown dwarfs (BDs) in the Galaxy. Their ubiquity poses a challenge to traditional models of star formation via gravitational fragmentation, because their masses are well below the typical Jeans mass in molecular clouds. Whether these cool objects form similarly to more massive stars or require additional processes is intensely debated (e.g., Burgasser et al. 2007; Luhman et al. 2007; Whitworth et al. 2007). Since multiplicity properties can provide insight into formation scenarios, it is of considerable interest to determine whether the properties of VLM binaries differ from those of more massive stars. Trends pertaining to VLM binaries are discussed at length by Burgasser et al. (2007). These systems are observed to be less frequent, more tightly bound, and of higher mass ratios than their more massive counterparts. It is not clear whether these properties form part of a continuous mass-dependent trend, or represent a unique population with a potentially different formation mechanism.

In recent years, much attention has been paid to relatively rare wide (greater than 100 AU) VLM binaries since their large separations and low binding energies provide direct constraints for formation models. In particular, their existence challenges the ejection model for the formation of VLM stars and BDs (Reipurth & Clarke 2001; Bate & Bonnell 2005) since such fragile systems are not expected to survive the ejection process.

To date there are eight known widely separated VLM and BD binaries, both in low-density star-forming regions (e.g., Luhman 2004; Allers et al. 2006; Jayawardhana & Ivanov 2006; Close et al. 2007; Luhman et al. 2009) and in the field (e.g., Gizis et al. 2000; Billères et al. 2005; Caballero 2007a; Béjar et al. 2008; Artigau et al. 2009). Surveys indicate a wide companion fraction for VLM stars and BDs of no more than 1%–2% (Burgasser et al. 2007; Caballero 2007b; Allen & Reid 2008). However, searches for ultracool binaries at the largest separations remain incomplete. The recent discovery of the widest

VLM binary by Artigau et al. (2007) with a separation of ~ 5100 AU and the discovery of a ~ 1800 AU binary by Caballero (2007a) point to the existence of a population of such ultrawide systems.

Here, we report the discovery of the widest VLM binary system to date with a projected separation of ~ 6700 AU.

2. DISCOVERY AND OBSERVATIONS

The system, comprised of 2MASS J12583501+4013083 and 2MASS J12583798+4014017 (2M1258AB hereafter), was found in a cross-match of the Sloan Digital Sky Survey (SDSS) 6th data release Photoprimary Catalog (Adelman-McCarthy et al. 2008) and the Two Micron All Sky Survey (2MASS) Point Source Catalog (PSC; Skrutskie et al. 2006) in which we searched for common proper motion pairs containing VLM components. The correlation of catalogs, calculation of proper motions, and the identification of comoving stars was done in overlapping sections of 4 deg^2 of the sky at a time, spanning the entire contiguous region of the SDSS Legacy Survey in the northern galactic cap. For every 2MASS source, the closest SDSS match was found and proper motion vectors with uncertainties were computed. A cut was made in order to select only stars that had moved at the 3σ level compared to all other stars within the area. Stars within $120''$ of one another with proper motion amplitudes agreeing within 2σ and proper motion components agreeing within 1σ in one of right ascension and declination were flagged as potential binaries. The pair 2M1258AB was found by applying further color cuts of $z' - J > 1.5$, corresponding approximately to mid- M spectral types and later to both components of potential binaries within our subsample.

To determine spectral types for the components of 2M1258AB, we obtained near-infrared (NIR) spectra ($R \sim 250$) on 2008 March 1 using the SpeX Medium-Resolution Spectrograph (Rayner et al. 2003) at NASA's Infrared Telescope Facility (IRTF). Observations were made in prism mode with the $0''.3$ slit. We obtained six 120 s exposures arranged in three AB cycles. For telluric and instrumental transmission correction,

Table 1
Multiple Epochs of Imaging Observations for 2M1258AB

| Source | Epoch (yr) | αA (deg) | αB (deg) | δA (deg) | δB (deg) |
|--------|------------|------------------|------------------|------------------|------------------|
| 2MASS | 1998.2666 | 194.645879(0.06) | 40.218994(0.08) | 194.658278(0.06) | 40.233826(0.08) |
| SDSS | 2003.3149 | 194.645997(0.05) | 40.218824(0.04) | 194.658460(0.06) | 40.233639(0.06) |
| CPAPIR | 2008.2292 | 194.646157(0.08) | 40.218670(0.08) | 194.658563(0.08) | 40.233519(0.08) |
| CPAPIR | 2008.4999 | 194.646156(0.08) | 40.218668(0.08) | 194.658549(0.08) | 40.233522(0.08) |

Notes. SDSS and 2MASS positions are taken directly from their respective catalogs. The uncertainties are given in the brackets, in units of arcseconds.

the A0 star HD 109615 was observed immediately after the target at the same air mass. The spectra were reduced using SpeXtool (Cushing et al. 2004; Vacca et al. 2003).

To confirm the common proper motion of this system, follow-up *J*-band imaging observations were obtained on 2008 March 25 and 2008 July 1 with the wide field NIR camera CPAPIR (E. Artigau et al. 2009, in preparation) at the 1.6 m Observatoire du Mont-Mégantic (OMM) telescope. At each visit, 16 exposures of 8.12 s were obtained by dithering the telescope by $\sim 5''$ between exposures. The follow-up *J*-band imaging data were reduced as follows. A sky frame was first constructed by taking the median of all images after masking the stars in each image. After subtraction of this sky frame, the images were divided by a normalized flat-field image. The distortion and astrometry solutions of each image were computed by using the 2MASS PSC as a reference frame. The reduced and calibrated images were then combined by taking their median. Astrometric uncertainties of ~ 80 mas were determined from the dispersion of the positions of all stars in the field with respect to their positions in the 2MASS PSC. The SDSS astrometry used was taken directly from the SDSS catalog. The positions reported by the catalog are derived from the *r'* band in which our sources are very faint. Therefore, as an additional check we calculated SDSS positions directly from the *i'* and *z'* images, and found them to be consistent with the catalog positions within the quoted uncertainties. A list of all astrometric measurements from OMM, SDSS, and 2MASS used to compute proper motions is listed in Table 1.

Proper motions and their uncertainties were obtained using an error-weighted linear regression, yielding proper motions for the primary and secondary, respectively, of 76 ± 8 mas yr $^{-1}$ and 76 ± 8 mas yr $^{-1}$ in right ascension, and -115 ± 9 mas yr $^{-1}$ and -108 ± 10 mas yr $^{-1}$ in declination. The proper motions are in agreement within the 1σ errors. The mean angular separation of the system was found to be $63''.38 \pm 0''.05$.

Using the space density for *M* dwarfs given by Phan-Bao et al. (2003) and our total search area of 7668 deg 2 , we would expect to find 1.8 pairs of *M6*–*M8* dwarfs within $64''$ of one another and at distances ranging from 75–125 pc (spectroscopic distances are derived in Section 3) within our search area. Using the space velocity distributions from Bochanski et al. (2005), the probability of any two *M* dwarfs having proper motions greater than $0''.1$ yr $^{-1}$ and agreeing within twice our uncertainties is 0.003. Therefore, we expect to find at most 0.0054 unrelated pairs similar to 2M1258AB in our entire search area, which implies a 99.5% probability of physical association for 2M1258AB.

For thoroughness, we note that the angular separation of 2M1258AB appears to increase monotonically over the three imaging epochs (2MASS, SDSS, CPAPIR) based on positions provided in Table 1. However, the trend falls within our uncertainties and is completely consistent with a constant separation over time. Furthermore, upon examination of the

Table 2
Physical Properties of 2M1258AB

| Quantity | A | B |
|---|---------------------------|---------------------------|
| 2MASS Designation | J12583501+4013083 | J12583798+4014017 |
| $\mu_{\alpha} \cos \delta$ (mas yr $^{-1}$) | 76 ± 8 | 76 ± 8 |
| μ_{δ} (mas yr $^{-1}$) | -115 ± 9 | -108 ± 10 |
| <i>J</i> (mag) ^a | 15.59 ± 0.05 | 15.61 ± 0.05 |
| <i>H</i> (mag) ^a | 14.84 ± 0.06 | 14.89 ± 0.06 |
| <i>K_s</i> (mag) ^a | 14.43 ± 0.06 | 14.62 ± 0.07 |
| <i>r'</i> (mag) ^b | 20.74 ± 0.04 | 22.00 ± 0.07 |
| <i>i'</i> (mag) ^b | 18.40 ± 0.02 | 19.18 ± 0.03 |
| <i>z'</i> (mag) ^b | 17.18 ± 0.02 | 17.68 ± 0.02 |
| <i>M_J</i> (mag) ^c | 10.20 ± 0.70 | 10.71 ± 0.41 |
| <i>M_H</i> (mag) ^c | 9.55 ± 0.64 | 10.07 ± 0.40 |
| <i>M_{K_s}</i> (mag) ^c | 9.17 ± 0.62 | 9.70 ± 0.37 |
| <i>d</i> (pc) | 115 ± 20 | 95 ± 18 |
| Spectral type | <i>M6</i> \pm 1 | <i>M7</i> \pm 1 |
| <i>T_{eff}</i> (K) ^d | 2850 ± 300 | 2620 ± 170 |
| Mass (<i>M_☉</i>) | $0.105^{+0.029}_{-0.017}$ | $0.091^{+0.011}_{-0.007}$ |
| Angular separation (''\$) | | 63.38 ± 0.05 |
| Projected separation (AU) | | 6700 ± 800 |
| Binding energy (10^{41} erg) | | 0.25 ± 0.08 |
| Mass ratio | | 0.87 ± 0.25 |

Notes.

^a Magnitudes from the 2MASS Point Source Catalog.

^b PSF magnitudes from the SDSS DR6 Catalog.

^c Estimates based on *M* dwarfs within ± 1 spectral type with measured parallaxes.

^d Based on the *T_{eff}* versus spectral type relationship of Golimowski et al. (2004)

2MASS ATLAS images, we find that this apparent trend is broken when measuring the angular separation directly from the *J* and *H* band images, and only holds using the *K_s*-band image. Therefore, the trend appears to be coincidental, and it remains most likely that the system is bound.

3. PHYSICAL PROPERTIES OF THE COMPONENTS

A summary of observational and physical properties of 2M1258AB is given in Table 2.

Spectral types for the components were determined primarily from the best-fitting reference spectra from the IRTF spectral library (Cushing et al. 2005). Reasonable fits were found from *M5*³–*M6.5* for the primary, and *M6.5*–*M8* for the secondary. Figure 1 shows our spectra of 2M1258AB plotted alongside those of other *M4*–*M9* dwarfs for comparison.

A weighted average of the H₂O A, B, and C indices⁴ defined by McLean et al. (2003) indicates spectral types of *M6* \pm 0.8

³ The *M5* match was to Gl 866ABC, which has an alternate classification of *M6* by Reid et al. (2004)

⁴ We have chosen not to include the H₂O D index as it predicts unreasonably early spectral types for both components, possibly a systematic effect of the telluric correction

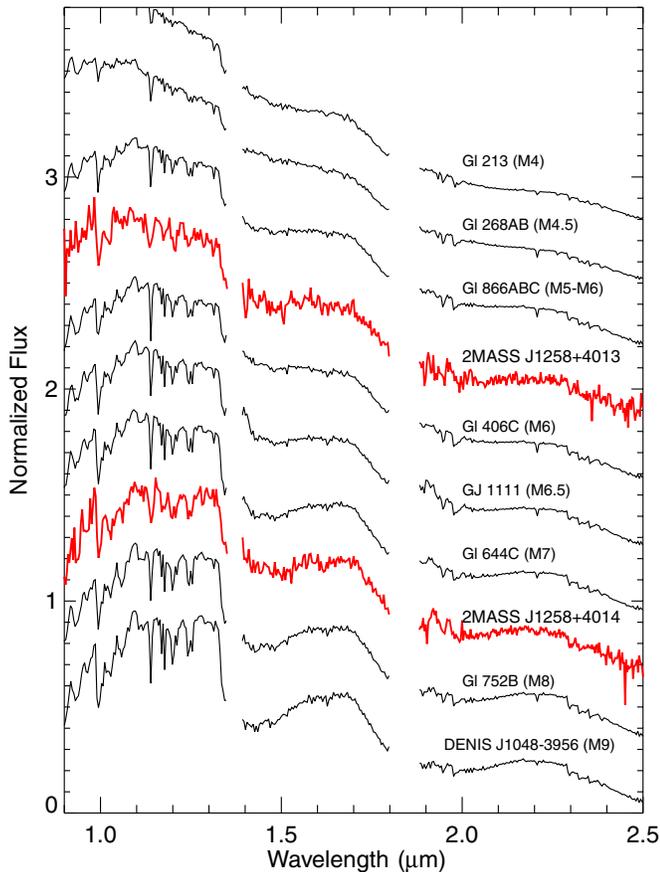


Figure 1. Spectra for 2M1258AB taken with the SpeX prism at the IRTF, alongside comparison spectra of field dwarfs from the IRTF spectral library (Cushing et al. 2005).

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

and $M7 \pm 0.8$ for the primary and secondary, respectively, in agreement with the former determination. Based on our fits to NIR reference spectra and the H_2O spectral indices, we assign spectral types of $M6 \pm 1$ for the primary and $M7 \pm 1$ for the secondary. The error bars are representative of the ambiguity present in assigning M dwarf spectral types based on low-resolution NIR spectra, as is evident from Figure 1.

In order to determine absolute J , H , and, K_s magnitudes and their associated uncertainties, we compiled a list of M dwarfs with measured parallaxes (Jao et al. 2005; Costa et al. 2006; Henry et al. 2006). From this list, M dwarfs with spectral types within 0.5 subclass of the component spectral types were used to determine mean absolute magnitudes for 2M1258AB, and the standard deviation of M dwarfs within 1.0 subclass was used as a measure of the uncertainty. By comparing our derived absolute magnitudes to the 2MASS J , H , and K_s magnitudes, we calculated spectroscopic distances for the components of 115 ± 20 pc and 95 ± 18 pc for the primary and secondary respectively. This implies a projected separation of 6700 ± 800 AU at the average system distance of 105 ± 13 pc.

The equivalent widths (EWs) of the $1.25 \mu\text{m}$ K I and $1.20 \mu\text{m}$ FeH features can be used as rough gravity indicators in NIR spectra. Using the wavelength regions defined by Gorlova et al. (2003), we measured the K I EWs to be 5.0 ± 1.7 , 10.6 ± 1.6 and the FeH EWs to be 12.9 ± 3.5 , 6.6 ± 3.2 for the primary and the secondary, respectively. When compared with Figure 8 of Gorlova et al. (2003), the measured EWs—with the exception of

the FeH EW in the secondary’s spectrum—are most consistent with that of field dwarfs with $\log g > 4.5$, and provide no evidence of youth. However, the large errors due to the low signal-to-noise ratio (S/N) of our spectra make it impossible to draw firm conclusions about the age or gravity of 2M1258AB. Assuming an age of 1–5 Gyr (as an upper limit; see Section 4) the component masses can be estimated from evolutionary models (Baraffe et al. 1998). Masses of $0.105^{+0.029}_{-0.017} M_\odot$ and $0.091^{+0.01}_{-0.007} M_\odot$ were found for the primary and secondary, respectively, by minimizing the error-weighted sum of square deviations between our derived absolute JHK_s magnitudes and the models, with errors bars representing 1σ deviations from the minimum. This determination is also consistent with masses derived from effective temperatures rather than magnitudes. The mass ratio of 2M1258AB is 0.87 ± 0.25 , consistent with other wide VLM binaries which tend to have mass ratios close to unity (Burgasser et al. 2007).

4. DISCUSSION

Of the previously known VLM binaries, only two have separations >1000 AU: Kōl AB with a separation of ~ 1800 AU (Caballero 2007b) and 2M0126AB with a separation of ~ 5100 AU (Artigau et al. 2007). In addition, a probable VLM binary with a separation of ~ 1700 AU has been identified by Caballero et al. (2006) in the σ Orionis cluster. With a separation of ~ 6700 AU, 2M1258AB is the widest VLM binary yet discovered (see Figure 2). The existence of 3–4 of such ultrawide systems is strong evidence that they are not statistically rare chance alignments, but rather natural outcomes of star formation.

Many other authors have discussed the implications of wide VLM binaries for various formation models (e.g., Luhman 2004; Artigau et al. 2007). As with other wide VLM binaries, 2M1258AB would have been disrupted by strong dynamical interactions during the formation process and thus would not have survived ejection. Despite this, simulations of star formation by Bate & Bonnell (2005) and Bate (2009) have produced a small number of VLM binaries with separations greater than 100 AU, and even a few with separations greater than 1000 AU (Bate 2009), through the simultaneous ejection of two VLM stars with similar velocities that subsequently become bound. However, these same simulations tend to overproduce VLM objects by a factor of ~ 4 compared to observations, and it remains unclear what effect this overproduction of VLM objects has on multiplicity properties. The formation of the secondary in the disk of the primary (e.g., Stamatellos et al. 2007; Boss 2000) can be strongly ruled out since disks around low-mass stars tend to be at most a few hundred AU in diameter (Vicente & Alves 2005), and tend to be only a few percent as massive as the stars they surround (Scholz et al. 2006). Thus, this mechanism is unlikely to produce near-equal mass binaries, nor binaries with such wide separations. Alternatively, since it is not uncommon for higher mass stars to form weakly bound binaries (e.g., Duquennoy & Mayor 1991), models in which VLM stars form similarly to their more massive counterparts are naturally able to account for the existence of wide VLM pairs. Turbulent fragmentation (Padoan & Nordlund 2002) is one such model, capable of producing low-mass cores down to ~ 3 Jupiter masses.

Higher order multiplicity may result in higher total system masses for wide VLM binaries, implying larger Jeans masses in formation. For more massive binaries, a large fraction ($\sim 25\%$) of wide (greater than 1000 AU) binaries are higher order multiples (Makarov et al. 2008). Of the two previously known ultrawide VLM binaries, at least one, Kōl AB, is a

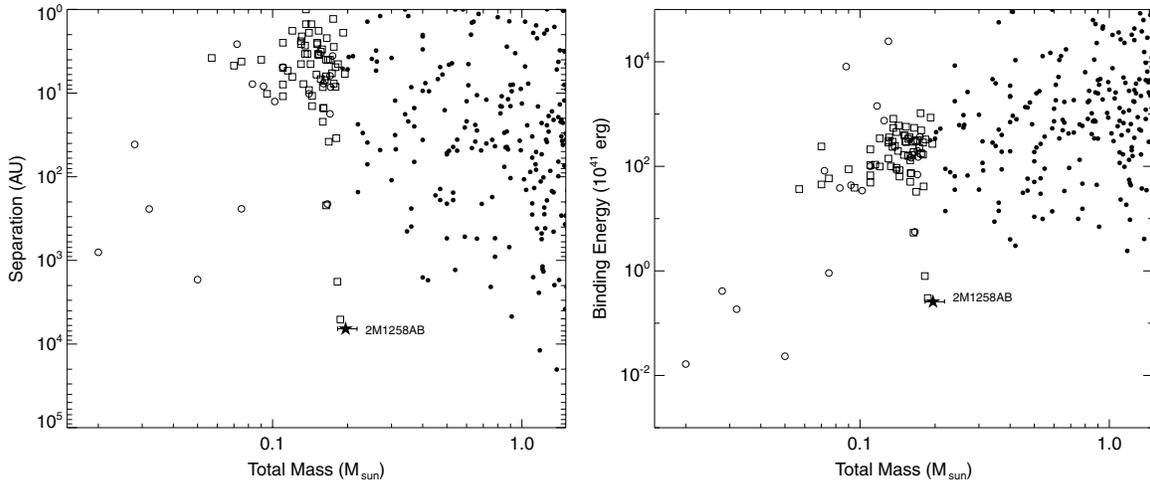


Figure 2. Separation and binding energy vs. total system mass for known binary systems. Stellar binaries (dots) are, from Tokovinin (1997); Fischer & Marcy (1992); Reid & Gizis (1997); Close et al. (1990); Kraus & Hillenbrand (2007). VLM binaries (open squares, open circles) are from Burgasser et al. (2007); Caballero et al. (2006); Luhman et al. (2009) and the VLM binary archive, maintained by Nick Siegler at <http://www.vlmbinaries.org>. Open circles identify VLM binaries that are known members of young associations.

candidate triple system, where the secondary is a suspected spectroscopic double with a total mass of $\sim 0.08 M_{\odot}$ (Basri & Reiners 2006). Other known examples among low-mass and VLM stars include: LP 213-68A(BC) with $M6.5$ and $M8$ components and a separation of 230 AU (Gizis et al. 2000; Close et al. 2003); G 124-62ABab, $M4.5/L1$, 1900 AU (Seifahrt et al. 2005); GJ 1245ABC, ($M5.5/M5.5$)/ $M8$, 38 AU (McCarthy et al. 1988); USco J160611.9-193532 AB, $M5/M5$, 1600 AU (Kraus & Hillenbrand 2007); and candidate triple LP 714-37ABC $M5.5/(M7/M8)$, 33 AU (Phan-Bao et al. 2006). Based on 2MASS and SDSS photometry there is some evidence that 2M1258AB may also be a triple system. Although the primary clearly has an earlier spectral type than the secondary (see Figure 1), the apparent J , H , and K magnitudes of the components are nearly identical. Referring to Table 3 of Hawley et al. (2002), we note that the difference in mean absolute J magnitude between $M6$ and $M7$ dwarfs is ~ 0.74 mag, suggesting that the secondary may itself be an unresolved equal-mass binary. If both K δ 1AB and 2M1258AB turn out to be triples then this would suggest that higher order multiplicity is common among the widest VLM systems. The second widest VLM binary, 2M0126AB, has yet to be checked for additional companions.

Wide weakly bound binaries such as 2M1258AB are subject to orbital evolution and eventual disruption as they travel through the Galaxy, due to encounters with stars and giant molecular clouds. Orbital evolution is an important consideration when assessing the probability that 2M1258AB formed in such a wide orbit, and also provides a rough constraint on the system age. The theoretical framework and numerical results for the evolution and lifetimes of wide binary systems in the solar neighborhood is provided by Weinberg et al. (1987), and can easily be scaled to apply to VLM systems (e.g., Artigau et al. 2007). From Figure 1a of Weinberg et al. (1987), the net effect of diffusive collisions is that an ensemble of wide systems will retain approximately the same average separation over time, provided they have not been disrupted. The dispersion in separation after ~ 1 Gyr is on the order of $\Delta \log a \approx \log 2$. Thus the orbital separation of wide VLM binaries remains approximately within a factor of 2 of the original separation. Even allowing for the possibility that binaries such as 2M1258AB as well as 2M0216AB were formed at half their current separation,

they would still have initial separations an order of magnitude greater than that of other wide VLM binaries and present the same challenges for formation scenarios. The disruption lifetimes of wide binaries are also of interest as they can provide upper limits on the system age. An order of magnitude estimate of the survival half-life, using Figure 2 of Weinberg et al. (1987) for a binary with $a/M_{\text{tot}} = 0.16 \text{ pc } M_{\odot}^{-1}$, yields $t_{1/2} \approx 1$ Gyr. If we assume the physical separation of the system to be greater than the projected separation then the survival half-life is slightly lower than this. Since it is unlikely that 2M1258AB is more than a few times older than $t_{1/2}$, the upper limit on the system age of 1–5 Gyr used for deriving masses in Section 3 is reasonable.

Further characterization of this system would benefit from optical spectra to better constrain the spectral types and activity of the components, as well as a parallax measurement to obtain a more accurate distance and hence separation. Both the primary and secondary should be checked for additional companions.

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