BD –22 5866: A LOW-MASS, QUADRUPLE-LINED SPECTROSCOPIC AND ECLIPSING BINARY

Evgenya Shkolnik
NASA Astrobiology Institute, Institute for Astronomy, University of Hawaii at Manoa, 2680 Woodlawn Drive, Honolulu, HI 96822; shkolnik@ifa.hawaii.edu

Michael C. Liu
Institute for Astronomy, University of Hawaii at Manoa, 2680 Woodlawn Drive, Honolulu, HI 96822; mlua@ifa.hawaii.edu

I. Null Reid
Space Telescope Science Institute, Baltimore, MD 21218; intr@stsci.edu

Leslie Hebb and Andrew C. Cameron
School of Physics and Astronomy, University of St. Andrews, North Haugh, St. Andrews, Fife KY16 9SS, Scotland, UK;
leslie.hebb@st-andrews.ac.uk, andrew.cameron@st-and.ac.uk

Carlos A. Torres
Laboratório Nacional de Astrofísica/MCT, Rua Estados Unidos 154, 37504-364 Itajubá, Brazil; beto@lna.br

David M. Wilson
Astrophysics Group, Keele University, Staffordshire ST5 5BG, UK; dw@astro.keele.ac.uk

Received 2007 November 14; accepted 2008 May 1

ABSTRACT
We report our discovery of an extremely rare, low-mass, quadruple-lined spectroscopic binary BD –22 5866 (=NLTT 53279, integrated spectral type = M0 V), found during an ongoing search for the youngest M dwarfs in the solar neighborhood. From the cross-correlation function, we are able to measure relative flux levels, estimate the spectral types of the components, and set upper limits on the orbital periods and separations. The resulting system is hierarchical, composed of a K7 + K7 binary and an M1 + M2 binary with semimajor axes of \( a_A \sin i_A \leq 0.06 \) and \( a_B \sin i_B \leq 0.30 \) AU. A subsequent search of the SuperWASP photometric database revealed that the K7 + K7 binary is eclipsing with a period of 2.21 days and an inclination angle of 85°. Within uncertainties of 5%, the masses and radii of both components appear to be equal (0.59 \( M_\odot \), 0.61 \( R_\odot \)). These two tightly orbiting stars (\( \alpha = 0.035 \) AU) are in synchronous rotation, causing the observed excess Ca II, Hα, X-ray, and UV emission. The fact that the system was unresolved with published adaptive optics imaging, limits the projected physical separation of the two binaries at the time of the observation to \( d_{AB} \leq 4.1 \) AU at the photometric distance of 51 pc. The maximum observed radial velocity difference between the A and B binaries limits the orbit to \( a_{AB} \sin i_{AB} \leq 6.1 \) AU. As this tight configuration is difficult to reproduce with current formation models of multiple systems, we speculate that an early dynamical process reduced the size of the system, such as the interaction of the two binaries with a circumquadruple disk. Intensive photometric, spectroscopic, and interferometric monitoring, as well as a parallax measurement of this rare quadruple system, is certainly warranted.

Subject headings: binaries: eclipsing — binaries: spectroscopic — stars: activity — stars: individual (BD –22 5866) — stars: late-type — stars: low-mass, brown dwarfs

Online material: color figures

1. INTRODUCTION
The multiplicity of stars is an important constraint of star formation theories, as most stars form as part of a binary or higher order multiple system (Duquennoy & Mayor 1991; Fischer & Marcy 1992; Halbwachs et al. 2003). Moreover, double- (or multi-) lined spectroscopic binaries (SBs) allow precise determination of dynamical properties including the mass ratio and, if the inclination can be determined, the individual component masses. And given their common age and metallicity, SBs are very useful in calibrating stellar evolutionary models.

Here, we report our detection of a visually unresolved, quadruple-lined spectroscopic and eclipsing (ESB4) binary BD –22 5866 (=NLTT 53279; \( V = 10.1, J_{\text{DMass}} = 7.54 \)) composed of four low-mass stars. As part of our search for young M dwarfs within 25 pc (E. Shkolnik et al. 2008, in preparation), we acquire high-resolution spectra of cool dwarfs compiled by the NStars project (Reid et al. 2002, 2004) that have X-ray luminosities comparable to or greater than Pleiades members. We cross-correlate these spectra with radial velocity (RV) standard stars in order to determine the RVs needed to measure galactic space motion. This process is sensitive to finding SBs, particularly those in short-period orbits, while the sample in general is biased toward tidally locked systems whose rapid rotation produces high chromospheric and X-ray emission. BD –22 5866 was on our list of candidate young stars: individual (BD –22 5866) — stars: late-type — stars: low-mass, brown dwarfs

Based on observations collected at the W. M. Keck Observatory and the Canada-France-Hawaii Telescope (CFHT). The Keck Observatory is operated as a scientific partnership between the California Institute of Technology, the University of California, and NASA, and was made possible by the generous financial support of the W. M. Keck Foundation. The CFHT is operated by the National Research Council of Canada, the Centre National de la Recherche Scientifique of France, and the University of Hawaii.

NASA Postdoctoral Fellow.

Alfred P. Sloan Research Fellow.
M dwarfs because of its high fractional X-ray and UV flux \((f_X/f_I = 1.94 \times 10^{-3}, f_{\text{NUV}}/f_I = 1.6 \times 10^{-4}, f_{\text{FUV}}/f_I = 3 \times 10^{-5})\) and photometrically determined distance of 20.7 ± 3.4 pc (Reid et al. 2004).

In this paper we decompose BD −22 5866 into a tight, hierarchical quadruple system consisting of an eclipsing K7 + K7 binary and an M1 + M2 binary, and discuss the implications of this extremely unusual multiple system for the dynamical evolution of binary stars. BD −22 5866 must be quite rare, since we detected only one such SB4 in our sample of 196 X-ray-selected M dwarfs. Other high-resolution spectroscopic surveys for SBs have turned up very few if any tight SB4s; e.g., Udry et al. (1998) surveyed 3347 G dwarfs and found none, while Torres et al. (2006) flagged two SB4s in a X-ray-selected sample of 1511 stars. Note that Torres et al.’s and our references therein.) We are aware of only one previously known spatially unresolved, quadruple-lined SB: XY Leo, a WUMa-type binary (Barden 1987; Pribulla et al. 2007), making BD −22 5866 (independently discovered, and the other (CPD −64 4353) is a higher mass system whose orbital limits are unconstrained. These limit the frequencies of SB4s to two in 40 grating orders covering 3700–10400 Å, respectively (White et al. 1999).

The velocity amplitude of the Neptune-mass planet orbiting GJ 436 is only 0.019 km s\(^{-1}\) (Butler et al. 2006), negligible for our purposes.

\(^{2}\) Values in italics represent those from CCF peaks that are strongly blended.

\(^{3}\) The RVs for these standards are published by Marcy & Benitz (1989), except GJ 821, which is from Nidever et al. (2002).

\(^{4}\) The velocity amplitude of the Neptune-mass planet orbiting GJ 436 is only 0.019 km s\(^{-1}\) (Butler et al. 2006), negligible for our purposes.

\(^{5}\) Details of this spectrum can be found in Torres et al. (2006).

\(^{6}\) The RVs for these standards are published by Marcy & Benitz (1989), except GJ 821, which is from Nidever et al. (2002).

\(^{7}\) The velocity amplitude of the Neptune-mass planet orbiting GJ 436 is only 0.019 km s\(^{-1}\) (Butler et al. 2006), negligible for our purposes.

\(^{8}\) Iraf (Image Reduction and Analysis Facility) is distributed by the National Optical Astronomy Observatory, which is operated by the Association of Universities for Research in Astronomy (AURA), Inc., under cooperative agreement with the National Science Foundation.

\(^{9}\) Since the Ca ii emission was clearly stronger in two of the four stars and potentially variable, it was important to eliminate the IRT from the cross-correlation.
absorption in the cross-correlation and removed a broad, low-order curvature from each CCF, which varies from order to order and is due to differences in the continuum between BD \(-22\) 5866 and the RV templates. A representative CCF for each of the four observations is shown in Figure 2.

We were able to clearly resolve the CCF peaks of all four stellar components on 2006 May 11. This allowed us to estimate the SpTs of the four stars assuming a flux-weighted relation (Cruz & Reid 2002) between component and integrated SpTs: \(\text{SpT}_{\text{int}} = (f_{\text{Aa}}\text{SpT}_{\text{Aa}} + f_{\text{Ab}}\text{SpT}_{\text{Ab}} + f_{\text{Ba}}\text{SpT}_{\text{Ba}} + f_{\text{Bb}}\text{SpT}_{\text{Bb}})/(f_{\text{Aa}} + f_{\text{Ab}} + f_{\text{Ba}} + f_{\text{Bb}})\), where \(f_{\text{Aa}}\), \(f_{\text{Ab}}\), \(f_{\text{Ba}}\), and \(f_{\text{Bb}}\) are derived from the integrated flux of the Gaussian fits to the four cross-correlation peaks. In this case, \(f_{\text{Aa}} \approx f_{\text{Ab}}\) and \(f_{\text{Ba}} \approx f_{\text{Bb}} \approx 0.3/f_{\text{Aa}}\), such that the difference in \(I\) magnitude between Aa and Ba is 1.2 mag. To measure the error associated with these relative fluxes, we cross-correlated the spectrum with three template spectra of stars with low \(v\sin i\) and differing SpTs. These were GJ 2079 (K7, \(v = 4.1\) km s\(^{-1}\), as calculated from \(P_{\text{rot}}\) of 7.78 days; Pizzolato et al. 2003), GJ 908 (M1, \(v\sin i = 3\) km s\(^{-1}\); Glebocki et al. 2000), and GJ 436 (M2.5, \(v\sin i \leq 1\) km s\(^{-1}\); Glebocki et al. 2000). The average results give \(f_{\text{Aa}} : f_{\text{Ab}} : f_{\text{Ba}} = 1 : 0.99 : 0.33 : 0.23\). These agree to better than 15%, with the bulk of the error lying with \(f_{\text{Bb}}\), whose integrated fluxes ranged from 0.2 to 0.3 of \(f_{\text{Aa}}\).

From the spectra alone, we estimated the component SpTs to be K7 + K7 and M1 + M2. These SpTs are consistent with the distinctly redder location of BD \(-22\) 5866 on a color-color diagram than expected if it were a single M0 dwarf. For example, it lies \(-0.7\) mag redder than expected for an M0 dwarf on a \((V - J)-(I - J)\) plot (Reid & Hawley 2005). BD \(-22\) 5866 is 3.7 times more luminous than a single M0 dwarf, and correcting for this overluminosity, the system’s photometric distance is at about 51 pc.

We measure the RVs (listed in Table 1) of each component from the Gaussian peaks fitted to the CCFs, taking the average of all orders, with a rms typically less than 1 km s\(^{-1}\). Severe blending of the CCF peaks resulted in poor Gaussian fits to the two latest observations. One additional set of RVs was extracted from a low-S/N spectrum collected using FEROS on La Silla’s 1.5 m telescope. The instrument and data reduction of this measurement are presented in Torres et al. (2006).

### 3. THE LIGHT CURVE

With the high eclipsing probability (>10%) of the tight Aa + Ab binary, we searched for existing photometry of this system in the database of the UK Wide-Angle Search for Planets (WASP) project. The WASP project is a wide-angle, robotic photometric monitoring campaign designed to detect significant numbers of transiting extrasolar planets using a single passband from 4000 to 7000 Å. The project instrumentation, infrastructure, and data processing are described in detail in Pollacco et al. (2006). In short, SuperWASP (La Palma, Canary Islands, Spain) and WASP-South (Sutherland, South Africa) instruments each consist of eight small-aperture camera lenses \((8 \times 200\) mm, f/1.8) backed by wide-format CCDs with a plate scale of 14.2 arcsec pixel\(^{-1}\). The cameras are attached to a single robotic mount, such that the field of view of a single WASP pointing is approximately 15° × 30°. The mount scans the sky taking repeated individual exposures in a single declination band over the observable sky every clear night to obtain a time series of images with typical sampling rate of \(-8\) minutes. The raw images are processed via a custom-built pipeline with aperture photometry performed using a 3.5 pixel aperture (48") on all observed stars. The resulting differential photometry light curves are searched for periodic dips in brightness using a modified box–least-squares search algorithm which is outlined in Collier Cameron et al. (2006).

The high-cadence, high-precision time series photometry produced for millions of bright stars as part the WASP transit survey is extremely good for detecting and characterizing EBs in...
addition to the primary science goal of transiting planet detection. The WASP-South data set on BD –22 5866 consists of 9531 photometric measurements obtained over two observing seasons (2006 May–2007 October). The observed light curve shows periodic ($P = 2.21$ days), nearly equal depth ($\approx 0.2$ mag) primary and secondary eclipses identifying the tight K7 + K7 pair as an EB. The raw WASP light curve is shown in Figure 3, phased according to the eclipse ephemeris (see Table 2). In addition to the eclipses, the photometry also exhibits modulating out-of-eclipse variability with an amplitude of 0.01–0.03 mag, which is likely caused by asymmetric starspots on the surface of the individual binary components. The measured period of this variability as determined from the strongest peak of the periodogram (Fig. 4) is nearly identical to the binary orbital period and tracks the rotation.

Fig. 2.—Cross-correlation function (with baseline removed) for BD –22 5866 as measured against a RV standard star on each of the four nights. The dashed curves are the Gaussians fitted to the CCF peaks.
of the star, indicating that the system is tidally synchronized. This
is expected, since the synchronization timescale for the short-
period binary A is only 70 Myr (Zahn 1977), several orders of
magnitude shorter than for binary B, making it the likely source
of the observed X-ray and UV flux. The RVs also confirm that
Aa and Ab are the sources of the moderate emission we see in
the magnitude shorter than for binary B, making it the likely source
period binary A is only 70 Myr (Zahn 1977), several orders of
is expected, since the synchronization timescale for the short-
of the star, indicating that the system is tidally synchronized. This

Due to the eclipsing nature of the K7 + K7 binary, the individual
stellar radii, temperature ratio, and orbital inclination can
be measured directly from the light curve. We first remove the
out-of-eclipse variability before modeling the eclipsing system
and deriving the physical properties of the individual stars.
Because the amplitude of the modulation is changing slowly over
the course of the observations, we separate the photometric data
into 3 week time bins and remove the variability of each segment
independently. For each time segment, we solve for the coefficients
of a sine curve that best fits the out-of-eclipse data using least-
squares minimization and then subtract this model from the
light curve. We tested 5000 frequencies between 0.4 and 20 days and found the
parameters of a sine curve (amplitude, phase, and zero-point offset) that best fit
the out-of-eclipse variability at each trial period. The peak at ≈2.2 days is clear,
which is nearly identical to the orbital period of the binary, thus indicating that the
stars are tidally locked.

4. THE ORBITAL CONFIGURATION

Although there are not many RV measurements, we can de-
termine well-constrained masses due to the accurate ephemeris
derived from the photometry. With the precise eclipse period, we are
able to plot our RV measurements to determine the remaining
orbital parameters for the K7 + K7 binary. To reduce the number of
fitted parameters needed to derive the component masses, we
adopt a mass ratio of 1.0 for the binary because the two com-
ponents have nearly the same flux and temperature values. We
solved for a single RV amplitude and systemic velocity
which best fit the Keck and CFHT RVs outside of eclipse. The 5 yr span
between the Mauna Kea and the La Silla observations is a sig-
nificant fraction of the A + B orbital period, and the correspond-
ing shift in γ due to the presence of binary B is apparent in the
offset of those points in Figure 6. The true systemic velocity of
the entire system is close to −9 km s⁻¹, measured by taking the average all observed RVs.

The mass for each K7 dwarf derived from the RV curve is
0.59 M☉. We estimate the uncertainty on this mass to be ≈5% based on the potential deviations from a mass ratio of 1. Additional
RV measurements will allow us to derive component masses with <1% accuracy. The relative flux levels of the CCF peaks
indicate that these two stars are in between a K7 and M0 dwarf, consistent with their derived masses. The system parameters are summarized in Table 2.

\begin{table}[h]
\begin{center}
\caption{Parameters for Binary Aa + Ab}
\begin{tabular}{lccc}
\hline
\textbf{Quantity} & \textbf{Value} & \textbf{Error} \\
\hline
Period (days) & 2.21107(5) & 0.000004 \\
Epoch (JHD – 2,450,000) & 3937.5900(0) & 0.00041 \\
$i$ (deg) & 85.5 & 1.0 \\
e & 0.00 & 0.01 \\
$\omega$ & 82° & ... \\
$R_{\text{Aa}}/a$ & 0.0814 & 0.0060 \\
$R_{\text{Ab}}/a$ & 0.0792 & 0.0058 \\
$T_{\text{eff, Aa}}/T_{\text{eff, Ab}}$ & 0.98 & 0.02 \\
$M_{\text{Aa}}/M_{\text{Ab}} (M_{\odot})$ & 0.5881 & 0.029 \\
$a$ (AU) & 0.0351 & 0.0024 \\
$R_{\text{Aa}} (R_{\odot})$ & 0.614 & 0.045 \\
$R_{\text{Ab}} (R_{\odot})$ & 0.598 & 0.045 \\
\hline
\end{tabular}
\end{center}
\end{table}

\textsuperscript{a} With an eccentricity of 0, the angle of periastron $\omega$ is very poorly constrained.
This pair is only the thirteenth confirmed EB with component masses less than 0.7 \( M_\odot \). Having model-independent masses and radii for both components is an essential part of testing stellar evolution models (Baraffe et al. 1998). Although the measured properties of the K7 binary components are consistent with being on the main sequence, the two stars appear 10%–20% larger in radii for their masses than predicted by the stellar evolution models (Fig. 7), in agreement with recent measurements of the other low-mass EBs with 10%–20% larger radii than expected. (See Table 3.)

Some empirical data suggest this is due to the effects of magnetic activity (López-Morales 2007), while other data show no correlation with activity, and instead find metallicity to be the dominant cause (Berger et al. 2006).

With regard to the rest of the quadruple system, the maximum velocity separation measured for the lower mass pair (Ba + Bb) is 52 \( \pm 0.8 \) km s\(^{-1}\). This, coupled with the estimated SpTs (and masses 0.49 and 0.44 \( M_\odot \) for an M1 and M2 dwarf, respectively; Reid & Hawley 2005), allows us to set upper limits on its orbital period and semimajor axis of 62 days and 0.30 AU. Although there is no indication of eclipses for this wider binary, we cannot determine if Ba and Bb are in a coplanar orbit with binary A.

With a grazing eclipse angle of >89°, Ba + Bb would not exhibit eclipses even if coplanar with Aa + Ab.

On 2006 May 11, we observed a maximum relative orbital velocity of 17.5 ± 2.3 km s\(^{-1}\) for the A and B binaries. If we treat the system as two single objects in Keplerian orbit, then this velocity measurement sets an upper limit of \( a_{AB} \sin i_{AB} \leq 6.1 \) AU and \( P_{AB} \leq 3764 \) days. At this separation, the binary pair A + B is resolvable with ground-based adaptive optics imaging.\(^{11}\) However, the change in \( \gamma \) of \( \approx 17 \) km s\(^{-1}\) in the 5 yr between observations implies that the period is likely closer to 6 yr (and then \( a_{AB} \sin i_{AB} \approx 4 \) AU) rather than the 10 yr of the maximal orbit.

A schematic of this ESB4 with its limiting orbital parameters is shown in Figure 8. In order to use the empirical criterion for the orbital stability of binary systems (Eggleton & Kiseleva 1995), we approximate this system to be a hierarchical triple by treating the

\(^{11}\) Daemgen et al. (2007) observed BD –22 5866 to have no physical companions within 0.08” using adaptive optics, setting an upper limit on the physical separation between A and B of \( d_{AB} < 4.1 \) AU at 51 pc from Earth at the observed orbital phase.

![Fig. 5.— Rectified light curves for the Aa (left) and Ab (right) eclipses of BD –22 5866 with the best model fit. [See the electronic edition of the Journal for a color version of this figure.]](image)

![Fig. 6.— Five RVs measured for Aa (circles) and Ab (squares) of BD –22 5866. The best-fit sine curves assume \( e = 0 \) and equal velocity amplitudes, and is fit only to the Mauna Kea data (white points) outside of eclipse. The La Silla data are plotted as black points and display a significant shift in \( \gamma \) due to the orbital motion of the two binaries. Measurement errors in both RV and phase are within the size of the points. The fits give \( K_{Aa} = K_{Ab} = 86.3 \) km s\(^{-1}\) and \( \gamma = -5.1 \) km s\(^{-1}\).](image)

![Fig. 7.— Mass vs. radius for known main-sequence EBs with masses \( M < 0.7 \) \( M_\odot \). The new M dwarf EB components, BD –22 5866 Aa and Ab, are shown as filled circles. The literature data on known M dwarf –M dwarf EBs (open circles) are taken from the references listed in Table 3. The lines show the theoretical, solar metallicity mass-radius relation with ages of 10 Myr (dot-dashed), 50 Myr (dashed), 500 Myr (dotted), and 5 Gyr (solid) (Baraffe et al. 1998).](image)

No. 2, 2008

BD –22 5866: A LOW-MASS ESB4

1253
drawn nearly to scale. See the electronic edition of the Journal for a color figure.

5. A NEED FOR A PRIMORDIAL CIRCUMQUADRUPLE DISK?

In order to reproduce the typical observed separations of ~40 AU in binary systems, Sterzik et al. (2003) determined that a multiple star system must undergo a phase of dynamical evolution after the fragmentation stemming from isothermal collapse of the molecular cloud. However, the formation of very close binaries with a of order 1 AU, as is the case for BD −22 5866 AB, is still somewhat unclear. Tokovinin et al.’s (2006) determination that the vast majority of short-period binaries must have tertiary components with which angular momentum can be exchanged may explain the tight orbit of Aa + Ab, yet also implies that $a_{AB}$ must have been even smaller in the past. This same argument may imply that a distant fifth component to the system might have interacted with binaries A and B to bring them to their small separation. However, no common proper-motion companions were found within 2000 AU of the system. We speculate that an earlier dynamical process reduced the physical size of the system, such as binary-disk interactions within a circumquadruple disk.

This is supported by the simulations by Bate et al. (2002) of binary and triple star formation, which predict the shrinking of orbital distances to ≤10 AU through accretion and interactions with circumbinary and circumtriple gas-rich disks on the timescale of less than 10^5 yr. However, in the case of a hierarchical triple, the tertiary component is always in a wide orbit of more than 30 AU from the tight binary. They also calculate that the specific angular momentum exchange will drive the masses of the two components toward equality, which is marginally the case for the A and B binaries of BD −22 5866, which has a mass ratio $q ≈ 0.7$.

There is no theoretical discussion in the literature regarding circumquadruple disks around low-mass stars. Yet it is reasonable to assume that BD −22 5866 must have once had such a gas-rich primordial disk, which likely lasted for less than 10^5–10^6 yr (Artymowicz & Lubow 1994). This would imply that the components accumulated their masses and interacted dynamically...

---

| Name                  | Mass ($M_\odot$) | $\delta M$ ($M_\odot$) | $R$ ($R_\odot$) | $\delta R$ ($R_\odot$) | References        |
|-----------------------|-----------------|------------------------|-----------------|------------------------|--------------------|
| RX J0239.1 A          | 0.730           | 0.009                  | 0.741           | 0.004                  | López-Morales & Shaw (2007) |
| RX J0239.1 B          | 0.693           | 0.006                  | 0.703           | 0.002                  |                    |
| 2MASS J01520930+0053266 A | 0.66           | 0.03                   | 0.64            | 0.08                   | Becker et al. (2008) |
| 2MASS J01520930+0053266 B | 0.62           | 0.03                   | 0.61            | 0.09                   |                    |
| GU Boo A              | 0.610           | 0.007                  | 0.623           | 0.016                  | López-Morales & Ribas (2005) |
| GU Boo B              | 0.599           | 0.006                  | 0.62            | 0.02                   |                    |
| YY Gem A              | 0.599           | 0.0047                 | 0.6191          | 0.0057                 | Delfosse et al. (1999) |
| YY Gem B              | 0.599           | 0.0047                 | 0.6191          | 0.0057                 |                    |
| BD −22 5866 Aa        | 0.588           | 0.029                  | 0.614           | 0.045                  | This work          |
| BD −22 5866 Ab        | 0.588           | 0.029                  | 0.598           | 0.045                  |                    |
| NSVS 01031772 A       | 0.5428          | 0.0027                 | 0.526           | 0.0028                 | López-Morales (2006) |
| NSVS 01031772 B       | 0.4982          | 0.0025                 | 0.5088          | 0.0003                 |                    |
| UNSW-TR-2 A           | 0.529           | 0.035                  | 0.641           | 0.05                   | Young et al. (2006) |
| UNSW-TR-2 B           | 0.512           | 0.035                  | 0.608           | 0.06                   |                    |
| Tres-Her0-07621 A     | 0.493           | 0.003                  | 0.453           | 0.06                   | Creevey et al. (2005) |
| Tres-Her0-07621 B     | 0.489           | 0.003                  | 0.452           | 0.06                   |                    |
| 2MASS 04463285+1901432 A | 0.47         | 0.05                   | 0.56            | 0.02                   | Hebb et al. (2006) |
| 2MASS 04463285+1901432 B | 0.19           | 0.02                   | 0.21            | 0.01                   |                    |
| OGLE BW3 V38 A        | 0.44            | 0.07                   | 0.51            | 0.04                   | Maceroni & Montalbán (2004) |
| OGLE BW3 V38 B        | 0.41            | 0.09                   | 0.44            | 0.06                   |                    |
| CU Cnc A              | 0.433           | 0.0017                 | 0.4317          | 0.0052                 | Delfosse et al. (1999) |
| CU Cnc B              | 0.389           | 0.0014                 | 0.3908          | 0.0094                 |                    |
| SDSS-MEB-1 A          | 0.272           | 0.02                   | 0.268           | 0.009                  | Blake et al. (2008) |
| SDSS-MEB-1 B          | 0.240           | 0.022                  | 0.248           | 0.0084                 |                    |
| CM Dra A              | 0.2307          | 0.001                  | 0.2516          | 0.002                  | Metcalfe et al. (1996) |
| CM Dra B              | 0.2136          | 0.001                  | 0.2347          | 0.0019                 |                    |

---

Fig. 8.—Maximal orbit of the low-mass, quadruple-lined SB, BD −22 5866, drawn nearly to scale. [See the electronic edition of the Journal for a color version of this figure.]
with each other (Sterzik et al. 2005) and their disk during the same early stages of their evolution. A systematic interferometric investigation of young, pre-main-sequence stars to search for additional low-mass, quadruple systems will help to test our hypothesis of stellar interactions with a circumquadruple disk, since these very young systems should be wider.

6. FUTURE OBSERVATIONS

Since the BD $\sim 22$ 5866 system is both bright and contains short orbital periods, we encourage those actively monitoring binaries to include this low-mass system in their programs. Spectroscopic monitoring will yield the component velocities for which specially designed techniques, such as the broadening function formulism of Rucinski (2002) or the four-dimensional cross-correlation method by Torres et al. (2007), are well suited. These are necessary to determine the Keplerian orbital parameters, which will provide more accurate mass ratios, and if the two remaining inclinations can be measured, the masses of the individual components, arguably the most important stellar property in the context of stellar evolution (e.g., interferometric observations [i.e., Boden et al. 2005] offer very high spatial resolution and could measure the separation and inclination of the A + B system). In addition, a parallax measurement to determine a more accurate distance to the system would be very beneficial.

With the potential of these observations to yield all four stellar masses as well as the three orbital inclinations, the BD $\sim 22$ 5866 system could provide key constraints to possible formation scenarios, as well as the ability to test the hypothesis that orbital evolution within a disk would create coplanar orbits (Bonnell & Bate 1994). Clearly, intensive follow-up observations of this rare eclipsing SB4 are warranted.

Note added in manuscript.—Katelyn Allers, Michael Liu, and Trent Dupuy imaged the ESB4 on 2008 May 28, using the Keck AO system. The two binaries were well resolved with $\Delta H = 0.9$ mag and a separation of 104 mas corresponding to $\approx 5.3$ AU.

E. S. appreciates useful discussion with George Herbig, Slavek Rucinski, Katelyn Allers, and Nader Haghhihipour, as well as helpful suggestions from the anonymous referee. Also, thank you to Nick Dunstone for his quick and independent discovery of the eclipses in the WASP database, and to the CFHT and Keck staff for their care in setting up the instruments and support in the control room. Research funding from the NASA Postdoctoral Program (formerly the NRC Research Associateship) for E. S. is gratefully acknowledged. This material is based on work supported by the National Aeronautics and Space Administration through the NASA Astrobiology Institute and the NASA/GALEX grant program under Cooperative Agreement Nos. NNA04CC08A and NNX07AJ43G issued through the Office of Space Science. M. C. L. acknowledges support from the Alfred P. Sloan Research Fellowship.

REFERENCES

Artymowicz, P., & Lubow, S. H. 1994, ApJ, 421, 651
Baraffe, I., Chabrier, G., Allard, F., & Hauschildt, P. H. 1998, A&A, 337, 403
Barden, S. C. 1987, ApJ, 317, 333
Bate, M. R., et al. 2002, MNRAS, 336, 705
Becker, A. C., et al. 2008, MNRAS, 386, 416
Berger, D. H., et al. 2006, ApJ, 644, 475
Blake, C. H., Torres, G., Bloom, J. S., & Gaudi, B. S. 2008, ApJ, 683, in press
Boden, A. F., et al. 2005, ApJ, 635, 442
Bonelli, E. L., & Bate, M. R. 1994, MNRAS, 269, L45
Butler, R. P., et al. 2006, ApJ, 646, 505
Collier Cameron, A., et al. 2006, MNRAS, 373, 799
Creevey, O. L., et al. 2005, ApJ, 625, L127
Cruz, K. L., & Reid, I. N. 2002, AJ, 123, 2828
Daemgen, S., Siegler, N., Reid, I. N., & Close, L. M. 2007, ApJ, 654, 558
Delfosse, X., Forveille, T., Mayor, M., Burnet, M., & Perrier, C. 1999, A&A, 341, L63
Donati, J.-F., Catala, C., Landstreet, J. D., & Petit, P. 2006, in ASP Conf. Ser. 358, Solar Polarization 4, ed. R. Casini & B. W. Lites (San Francisco: ASP), 362
Donati, J.-F., et al. 1997, MNRAS, 291, 658
Duquennoy, A., & Mayor, M. 1991, A&A, 248, 485
Eggleton, P., & Kiseleva, L. 1995, ApJ, 455, 640
Fischer, D. A., & Marcy, G. W. 1992, ApJ, 396, 178
Fitzpatrick, M. J. 1993, in ASP Conf. Ser. 52, Astronomical Data Analysis Software and Systems II, ed. R. J. Hanisch, R. V. J. Brissenden, & J. Barnes (San Francisco: ASP), 472
Giebcki, R., Gmaciński, P., & Stawikowski, A. 2000, Acta Astron., 50, 509
Halbwachs, J.-L., Mayor, M., Udry, S., & Arenou, F. 2003, A&A, 397, 159
Hebb, L., Wyse, R. F. G., Gilmore, G., & Holtzman, J. 2006, AJ, 131, 555
López-Morales, M. 2006, PASP, 118, 716
———. 2007, ApJ, 600, 732
López-Morales, M., & Ribas, I. 2005, ApJ, 631, 1120
López-Morales, M., & Shaw, J. S. 2007, in ASP Conf. Ser. 362, The Seventh Pacific Rim Conference on Stellar Astrophysics, ed. Y.-W. Kang et al. (San Francisco: ASP), 26
Maceroni, C., & Montalban, J. 2004, A&A, 426, 577
Marcy, G. W., & Benitz, K. J. 1989, ApJ, 344, 441
Metalaff, T. S., Mathieu, R. D., Latham, D. W., & Torres, G. 1996, ApJ, 456, 356

Morrison, P., et al. 2007, ApJS, 173, 682
Nidever, D. L., Marcy, G. W., Butler, R. P., Fischer, D. A., & Vogt, S. S. 2002, ApJS, 141, 503
Pizzolato, N., Maggio, A., Micela, G., Sciortino, S., & Ventura, P. 2003, A&A, 397, 147
Pollacco, D. L., et al. 2006, PASP, 118, 1407
Popper, D. M., & Ezel, P. B. 1981, AJ, 86, 102
Pribulla, T., et al. 2006, AJ, 132, 769
———. 2007, AJ, 133, 1977
Reid, I. N., Gizis, J. E., & Hawley, S. L. 2002, AJ, 124, 2721
Reid, I. N., & Hawley, S. L. 2005, New Light on Dark Stars: Red Dwarfs, Low-Mass Stars, Brown Stars (Chichester: Praxis), 314
———. 2004, AJ, 128, 463
Rucinski, S. M. 2002, AJ, 124, 1746
Skrutskie, M. F., et al. 2006, AJ, 131, 1163
Southworth, J., Maxted, P. F. L., & Smalley, B. 2004, MNRAS, 349, 547
Sterzik, M. F., Durisen, R. H., & Zinnecker, H. 2003, A&A, 411, 91
Sterzik, M. F., Melo, C. H. F., Tokovinin, A. A., & van der Bliek, N. 2005, A&A, 434, 671
Strassmeier, K. G., Hall, D. S., Feke, F. C., & Scheck, M. 1993, A&AS, 100, 173
Tokovinin, A. A. 1997, A&AS, 124, 75
Tokovinin, A., Thomas, S., Sterzik, M., & Udry, S. 2006, A&A, 450, 681
Torres, C. A. O., Quast, G. R., da Silva, L., de la Reza, R., & Melo, C. H. F. 2006, A&A, 460, 695
Torres, G., Latham, D. W., & Stefanik, R. P. 2007, ApJ, 662, 602
Udry, S., et al. 1998, in ASP Conf. Ser. 154, Cool Stars, Stellar Systems and the Sun: Tenth Cambridge Workshop, ed. R. A. Donahue & J. A. Bookbinder (San Francisco: ASP), 2148
Voges, W., et al. 1999, A&A, 349, 389
Vogt, S. S., et al. 1994, Proc. SPIE, 2198, 362
White, R. J., Ghez, A. M., Reid, I. N., & Schultz, G. 1999, ApJ, 520, 811
Wilking, B. A., Meyer, M. R., Robinson, J. G., & Greene, T. P. 2005, AJ, 130, 1733
Young, T. B., Hidas, M. G., Webb, J. K., Ashley, M. C. B., Christiansen, J. L., Derekas, A., & Nuttel, C. 2006, MNRAS, 370, 1529
Zacharias, N., Monet, D. G., Levine, S. E., Urban, S. E., Gaume, R., & Wycoff, G. L. 2005, BAES, 36, 1418
Zahn, J.-P. 1977, A&A, 57, 383