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An Age Constraint for the Very Low-Mass Stellar/Brown Dwarf Binary 2MASS J03202839−0446358AB

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ABSTRACT

2MASS J03202839−0446358AB is a recently identified, late-type M dwarf/T dwarf spectroscopic binary system with both primary radial velocity orbit and component spectral types determined. Coupled with the age-dependent luminosity of the brown dwarf secondary, these measurements enable a robust constraint on the age of a very low-mass star and a brown dwarf in the field. We determine a minimum age of 2.0±0.3 Gyr for this system, corresponding to minimum primary and secondary masses of 0.080 $M_\odot$ and 0.053 $M_\odot$ (respectively), based on comparisons to four different sets of evolutionary models. Consistency between the model parameters indicate broad agreement in current theoretical predictions for evolved very low-mass dwarfs, although we are not able to independently assess their accuracy. The inferred minimum age is qualitatively consistent with the kinematics and activity of this system but not the rapid rotation of its primary, adding to evidence of a breakdown in angular momentum evolution trends amongst the lowest luminosity stars. Assuming a maximum age of 10 Gyr, we further constrain the orbital inclination of this system to $i \gtrsim 53°$. Future observations of 2MASS 0320−0446AB to determine its orbital inclination, either by resolving the system and measuring its astromeric orbit or detection of an eclipse, or to determine its component mass ratio would yield a bounded age determination more precise than current empirical age/secondary parameter relations.

Subject headings: stars: binaries: general — stars: fundamental parameters — stars: individual (2MASS J03202839−0446358) — stars: low mass, brown dwarfs

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1. Introduction

Of the three most fundamental parameters of a star—mass, age and composition—age is the most difficult to obtain an accurate measure. Direct measurements of mass (e.g., orbital motion, microlensing, asteroseismology) and atmospheric composition (e.g., spectral analysis) are possible for individual stars, but age determinations are generally limited to the coeval stellar systems in which stellar evolutionary effects can be exploited (e.g., pre-main sequence contraction, isochronal ages, post-main sequence turnoff). Individual stars can be approximately age-dated using empirical trends in magnetic activity, element depletion, rotation or kinematics that are calibrated using cluster populations and/or numerical simulations (e.g., Wilson & Wooley 1970; Skumanich 1972; Wielen 1977; Barnes 2007; West et al. 2008). However, such trends are fundamentally statistical in nature, and source-to-source scatter can be comparable in magnitude to mean values. Age uncertainties are more problematic for low-mass stars, which dominate the Galactic disk population. For these sources, post-main sequence evolution occurs at ages much greater than the Galactic age, while pre-main sequence stars are generally confined to young star-formation regions and associations. For the vast majority of intermediate-aged (1–10 Gyr) low-mass stars in the Galactic disk, barring a few special cases (e.g., low-mass companions to cooling white dwarfs; Silvestri et al. 2006) age determinations require the use of low-precision empirical trends.

Ages are of particular importance for even lower-mass brown dwarfs, objects which fail to sustain core hydrogen fusion and therefore cool and dim over time (Kumar 1962; Hayashi & Nakano 1963). The cooling rate of a brown dwarf is set by its age-dependent luminosity, while its initial reservoir of thermal energy is determined from gravitational contraction and hence total mass. As such, there is an inherent degeneracy between the mass, age and luminosity (or spectral type) of a given brown dwarf observed in the vicinity of the Sun. This degeneracy may be broken for individual sources through measurement of secondary parameters such as surface gravity (e.g., Mohanty et al. 2004; Burgasser, Burrows & Kirkpatrick 2006; Leggett et al. 2007; Cushing et al. 2008) or the absence or presence of Li I absorption (depleted in brown dwarfs more massive than 0.065 $M_{\odot}$ for ages $\gtrsim$200 Myr; Rebolo, Martín, & Magazzu 1992; Bildsten et al. 1997). In such cases, mass and age determinations are possible through comparison of observed physical parameters to bulk evolutionary models. Such determinations are highly dependent on the accuracy of atmospheric models, which are known to have systematic problems at low temperatures due to incompleteness in molecular opacities or non-equilibrium dynamics (e.g., Smith et al. 2003; Cushing et al. 2008).

Binary systems containing brown dwarf components can be used to break this mass/age degeneracy without resorting to atmospheric models. Specifically, systems for which mass determinations can be made via astrometric and/or spectroscopic orbit measurements, and component spectral types and/or luminosities determined, can be compared directly with evolutionary models to uniquely determine the system age. Furthermore, by comparing the inferred ages and masses for each presumably coeval component, such systems can provide empirical tests of the evolutionary models themselves. A benchmark example is the young (∼300 Myr) binary (and perhaps triple) brown dwarf companion system Gliese 569B (Martín et al. 2000; Lane et al. 2001; Zapatero Osorio et al. 2004, 2005; Simon, Bender & Prato 2006). With both astrometric and spectroscopic orbit determinations, and resolved component spectroscopy, this system has been used to explicitly test evolutionary model tracks and lithium burning timescales (Zapatero Osorio et al. 2004, 2005) as well as derive component ages, which are found to agree qualitatively with kinematic arguments (e.g., Kenworthy et al. 2001). Other close binaries with astrometric or spectroscopic orbits have also been used for direct mass determinations (e.g., Bouy et al. 2004; Stassun et al. 2006; Joergens & Müller 2007; Ireland et al. 2008; Liu, Dupuy & Ireland 2008), but these systems generally lack resolved spectroscopy and therefore precise component characterization. Systems for which orbit measurements have been made to date also tend to be young, preventing stringent tests of the long-term evolution of cooling brown dwarfs. Older, nearby binaries with resolved spectra (e.g., Burgasser & McElwain 2006; McElwain & Burgasser 2006; Martín et al. 2006) generally have prohibitively long orbital periods for mass determinations.

Recently, we have identified a binary system that straddles the regime for which a spectroscopic orbit and component spectral types can be determined: the late-type dwarf 2MASS J03202839−0446358 (hereafter 2MASS J0320−0446; Cruz et al. 2003; Wilson et al. 2003). Our independent discoveries of this system were made via two complementary methods. Blake et al. (2008, hereafter Bl08) identified this source as a single-lined radial velocity variable following roughly 3 years of high-resolution, near-infrared spectroscopic monitoring (see Blake et al. 2007). Burgasser et al. (2008, hereafter Bu08) demonstrated that the peculiar low-resolution, near-infrared spectrum of this source could be reproduced as an M8.5 plus T5±1 unresolved pair, following the technique outlined in Burgasser (2007b). The methods used by these studies have yielded both mass and spectral type constraints for the components of 2MASS J0320−0446, and thus a rare opportunity to robustly constrain the age of a low-mass star and a brown dwarf in the Galactic disk.

In this article, we determine a lower limit for the age of 2MASS J0320−0446 by combining the radial velocity results and component spectral type determinations with current evolutionary models. In § 2 we describe our analysis in detail, indicating major sources of uncertainty and comparing predictions from four sets of evolutionary models. We obtain lower limits on the age, component masses, and orbital inclination of the system. We also compare our age constraint to expectations based on the kinematics, rotation and activity of this system. In § 3 we discuss our results, focusing on how future observations may provide a bounded determination on the age of this system.

2. The Age of 2MASS J0320−0446

2.1. Component Luminosities

Evolutionary models predict the luminosities and effective temperatures of cooling brown dwarfs over time, parameters which have been shown to correlate with spectral type (e.g., Kirkpatrick et al. 2000; Golimowski et al. 2004; Nakajima, Tsuji & Yanagisawa 2004). Luminosity is the more reliably measurable parameter as it is based only on distance and broad-band spectral flux. However, in the case of 2MASS J0320−0446, neither distance nor component fluxes have been measured, the latter due to the fact that this system is as yet unresolved (and for the near future, unresolvable; see § 3). We therefore use the inferred component spectral types of this system from Bu08 and luminosity measurements for similarly-classified systems from Dahn et al. (2002); Golimowski et al. (2004); Vrba et al. (2004) and Cushing, Rayner & Vacca (2005) to estimate the component luminosities.

For the M8.5 primary, there are 13 M8–M9 field dwarfs with bolometric luminosities (parallax distance and broad-band spectral flux measurements) reported in the studies listed above. Two of the sources—the M8 LHS 2397a, a known binary (Freed, Close, & Siegler 2003); and the M9 LP 944-20, believed to be a younger system (∼500 Myr, Tinney 1998)—were rejected. The mean bolometric magnitude of the remaining sources is $\langle M_{bol}\rangle$ = 13.36±0.29 mag, corresponding to $\log_{10} L_{bol}/L_\odot$ = -3.45±0.12.

For the T5±1 secondary, there are fewer field brown dwarfs with reliable luminosity measurements (1 T4.5 dwarf and 5 T6 dwarfs) and these show much greater scatter in their bolometric magnitudes: $\langle M_{bol}\rangle$ = 17.2±0.6. The large scatter may be due in part to unresolved multiplicity, which appears to be enhanced amongst the earliest-type T dwarfs (Burgasser et al. 2006; Liu et al. 2006; Burgasser 2007a). Hence, we estimated the luminosity of 2MASS J0320−0446B using the M_{bol}/spectral type relation of Burgasser (2007a)[1]. A mean $\langle M_{bol}\rangle$ = 17.09±0.29 ($\log_{10} L_{bol}/L_\odot$ = -4.94±0.17) was adopted, where the uncertainty takes into account the uncertainty in the secondary spectral type and the M_{bol}/spectral type relation (0.22 mag). This value agrees well with estimates from Vrba et al. (2004, $\langle M_{bol}\rangle$ =

[1]The coefficients of this polynomial relation reported in Burgasser (2007a) did not list sufficient significant digits, resulting in slight differences between the numerical relation and that shown in Figure 1 of the paper. The coefficients as defined should be $\{c_i\}$ = [1.37376e1, 1.90250e-1, 1.73083e-2, 7.40013e-3, -1.75144e-3, 1.14234e-4, -2.32248e-06], where $M_{bol} = \sum_{i=0}^{6} c_i \mathrm{SpT}^i$ and SpT(T0) = 10, SpT(T5) = 15, etc.

16.9±0.4) and Golimowski et al. (2004, $\langle M_{bol} \rangle$ = 17.3±0.6).

2.2. Evolutionary Models

In order to assess systematic uncertainties in the derived age and component properties of the 2MASS J0320−0446 system, we considered four different sets of evolutionary models in our analysis: the cloudless models of Burrows et al. (1997, 2001, hereafter TUCSON models), the "COND" cloudless models of Baraffe et al. (2003, hereafter COND models), and the cloudless and cloudy models from Saumon & Marley (2008, hereafter SM08 models). All four sets of models assume solar metallicity; the composite red optical and near-infrared spectra of 2MASS J0320−0446 show no indications of significantly subsolar metallicities (Cruz et al. 2003, Bu08). The choice of "cloudless" evolutionary models (referring to the absence of condensate clouds in atmospheric opacities) is driven partly by availability, although Chabrier et al. (2000) have claimed that clouds have a "small effect" on the evolution of brown dwarfs. While it is true that the spectral energy distributions of the M8.5 and T5 components of 2MASS J0320−0446 are minimally affected by condensate cloud opacity (e.g., Allard et al. 2001), cloud opacity in the intermediate L dwarf stage may slow the radiative cooling timescale during this phase and bias the inferred age of the T-type secondary (Saumon & Marley 2008). We chose to test this possibility by examining both the cloudless and cloudy SM08 models, the latter of which takes into account photospheric cloud opacity in thermal evolution using atmospheric models generated according to the prescription outlined in Ackerman & Marley (2001) and SM08.

Figure 1 compares the luminosity estimates for the two components of 2MASS J0320−0446 to the evolutionary tracks of each model set. The luminosities (and their uncertainties) constrain the mass/age parameter space of each component, as illustrated in Figure 2. Component masses increase with system age, as more massive low mass stars and brown dwarfs take longer to radiate their greater reservoir of heat energy from initial contraction. The mass of the primary of this system reaches an asymptotic value of ∼0.08–0.09 $M_\odot$ for late ages, making it a hydrogen-fusing very low-mass star. If the system is younger than ∼700 Myr, the primary can be substellar. Ages $\lesssim$500 Myr (primary masses <0.065 $M_\odot$) can be ruled out based on the absence of Li I absorption at 6708 Å in the unresolved red optical spectrum of this source (Cruz et al. 2003). The mass of the secondary increases across the full age range shown in Figure 2 as this component is substellar up to 10 Gyr (although the TUCSON models suggest a hydrogen-burning mass at very late ages). Note the kink in the mass/age relation of this component at ages of 200-300 Myr, particularly in the COND and SM08 models. This reflects the prolonged burning of deuterium in brown dwarfs with masses just above 0.013 $M_\odot$, which slightly enhances already low luminosities at this stage of evolution. The mass ratio of the system, $q \equiv M_2/M_1$, also increases as a function of age, ranging from ∼0.2 at 100 Myr to a maximum of ∼0.8 at 10 Gyr.

2.3. Constraints from the Primary Radial Velocity Orbit

The radial velocity variations measured by Bl08 probe the recoil velocity of the primary of the 2MASS J0320−0446 system. These observations provide on constraint between the masses and inclination of the system of

$$M_2 \sin i = (0.2062 \pm 0.0034)(M_1 + M_2)^{2/3} \ \ M_\odot, \tag{1}$$

where i is the inclination angle of the orbit, and M_1 and M_2 the masses of the primary and secondary components in solar mass units, respectively. We can make a geometric constraint that $\sin i \leq 1$, which yields a transcendental equation for the lower limit of the secondary component mass of the system as a function of the primary component mass. Using our derived lower bound on the latter from the evolutionary models (including luminosity uncertainties) and the lower bound on $M_2 \sin i$ from the radial velocity measurements of Bl08, we determined the minimum secondary component mass as a function of system age. Finally, the age at which the upper bound of the secondary component mass (based on the evolutionary models) crosses the radial velocity minimum mass line corresponds to the minimum age of the system, as illustrated in Figure 2.

All four models predict roughly the same minimum age for 2MASS J0320−0446, roughly 1.7–2.2 Gyr (Table 1). This minimum age is in excellent qualitative and quantitative agreement with ages inferred from the kinematics of the 2MASS J0320−0446 system[2] and stellar age/activity trends. In the latter case, the optical spectrum of 2MASS J0320−0446 shows no detectable Hα emission (Cruz et al. 2003), even though >90% of nearby M8–M9 dwarfs exhibit such emission (Gizis et al. 2000; Schmidt et al. 2007; West et al. 2008). For comparison, West et al. (2008) estimate an "activity lifetime" (i.e., timescale for Hα emission to drop below detectable levels) of $8^{+0.5}_{-1.0}$ Gyr for M7 dwarfs.

However, 2MASS J0320−0446A is also a relatively rapid rotator, with $V \sin i = 16.5 \pm 0.5$ km s^{-1} and a rotation period < 7.4 hr (Bl08). According to standard stellar rotation trends, such

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[2]Combining the systemic radial velocity from Bl08 with the revised proper motion and distance estimates from Bu08, the UVW space motions of this system are U = -38±5 km s^{-1}, V = -20±3 km s^{-1} and W = -32±4 km s^{-1}, where we assume an LSR solar motion of $U_\odot$ = 10 km s^{-1}, $V_\odot$ = 5.25 km s^{-1} and $W_\odot$ = 7.17 km s^{-1} (Dehnen & Binney 1998). Wielen (1977), equation 8, predicts an age >1.6 Gyr at the 95% confidence level for these kinematics.

rapid rotation is unexpected as stars spin down with time due to angular momentum loss, predominately through magnetized stellar winds (e.g., Skumanich 1972; Soderblom, Duncan, & Johnson 1991). Again for comparison, extrapolating Equation 3 from Barnes (2007, assuming $B - V \approx 2.1$ for 2MASS J0320−0446A; e.g., Leggett 1992) yields a highly unrealistic age of ∼0.1 Myr. The loss of magnetic spin-down mechanisms in late-type dwarfs, possibly tied to a reduced buildup of magnetic stresses in increasingly neutral photospheres, has been suggested as an explanation for the generally rapid rotation of cooler L-type dwarfs in the vicinity of the Sun (e.g., Gelino et al. 2002; Mohanty et al. 2002; Mohanty & Basri 2003). Our age constraint for the rapidly rotating 2MASS J0320−0446A firmly supports a weakening in stellar spin-down mechanisms in the lowest-mass stars, and illustrates how some empirical age trends are simply unapplicable for low-mass field dwarfs.

The derived minimum age and radial velocity constraints of the 2MASS J0320−0446 system allows us to also determine (model-dependent) minimum masses for its components. Primary minimum masses span 0.080–0.082 $M_\odot$ and secondary minimum masses span 0.053–0.054 $M_\odot$. The limits on the secondary are primarily set by the radial velocity constraints. As with the minimum age, there is very little difference (<1%) in the component masses inferred between the four models examined; and, noteably, essentially no difference between the cloudy and cloudless SM08 models. The minimum mass ratio of the system, $q > 0.60$–0.62, is also consistent between the evolutionary models, and in accord with the general preference of large mass ratio systems amongst very low-mass binaries (>90% of known binaries with $M_1 < 0.1$ $M_\odot$ have $q > 0.6$; see Burgasser et al. 2007).

Finally, while the minimum ages and masses of 2MASS J0320−0446 are inferred assuming $\sin i \leq 1$, it is possible to make a constraint on the maximum masses and minimum orbital inclination of this system assuming an upper age limit. Adopting $\tau < 10$ Gyr, $\sin i >$ 0.80–0.86, corresponding to $i > 53°$–59°. This constraint is only slightly more restrictive than the $i > 44°$ lower limit determined by Bl08 assuming that the fainter secondary must have a lower mass than the primary, and does not significantly improve upon the relatively low probability that this system is an eclipsing edge-on system (∼0.3% by geometry). Maximum primary (0.088 $M_\odot$) and secondary masses (0.066–0.075 $M_\odot$) are effectively set by the luminosity constraints and evolutionary models. Here we see the most significant difference between the models, a 13% discrepancy in the maximum mass of the secondary component, likely due to different treatments of light element fusion near the Li- and H-burning minimum masses. Importantly, there is very little difference (∼4%) in the maximum masses inferred from the SM08 cloudy and cloudless models, confirming the negligible role of cloud opacity in the long term evolution of the most massive brown dwarfs.

3. Discussion

The combination of component luminosities, primary radial velocity orbit and evolutionary models have allowed us to make a lower limit constraint on the age of the 2MASS J0320−0446 system. This constraint is tied to the physical theory of cooling brown dwarfs, and can be considered more robust (albeit more model-dependent) than determinations based on statistical trends in kinematics, activity and angular momentum evolution. This is particularly the case given the remarkable agreement between the four evolutionary models examined here, and the dramatic disagreement between age-activity and age-rotation trends. Nevertheless, the derived age constraint remains limited by the unknown inclination of the system and uncertainty in the component luminosities. As discussed in Bl08, the inclination of the 2MASS J0320−0446 orbit is irrelevant if the radial velocity orbit of the secondary can be determined. In that case, one need only compare the derived system mass ratio to evolutionary model predictions based on the component luminosities. Measurement of the secondary motion in the K-band data of Bl08 was not possible, almost certainly due to the very large difference in flux between the components at these wavelengths (ΔK ∼4–5 mag; Bu08). A more effective approach would be the acquisition of radial velocity measurements in the 1.2-1.3 μm or 1.58–1.63 μm regions where the T dwarf secondary is considerably brighter.

Alternately, if this system is observed to eclipse, then $\sin i \approx 1$ and the age of the system is uniquely determined. Table 1 lists the ages corresponding to this scenario, ranging from $2.5^{+1.0}_{-0.7}$ Gyr to $3.2^{+1.3}_{-0.9}$ Gyr for the four models examined (uncertainties include the full range of possible primary and secondary masses for which Eqn. 1 and the luminosity constraints are satisfied). These values are again consistent, and notably to within relatively small uncertainties (25–60%), attributable entirely to the uncertainty in the component luminosities. Better luminosity determinations could be made through broadband resolved imaging of the system and parallax distance measurement. The former is currently unfeasible, as the radial velocity orbit predicts a tight separation, $a \sin i = a_1 \frac{1+q}{q} \sin i \approx 0.4$ AU (Bl08, assuming $q \approx 0.6$), or a projected separation of $\lesssim$17 mas at the distance of 2MASS J0320−0446 (∼25 pc; Cruz et al. 2003). This is below the diffraction limit of the Keck 10m telescope at near-infrared wavelengths. Diffraction-limited observations with larger (>25m) telescopes, or wide-baseline interferometers with better near-infrared sensitivity than current facilities, are required. Alternatively, a better constraint on the relative fluxes of the two components may be possible spectroscopically if the radial velocity signature of the secondary can be separated from the primary. In the current analysis, significant uncertainty in the secondary's luminosity can be attributed to the small number of mid-type T dwarfs with parallax and luminosity measurements to date. Hence, even better characterization of the bolometric luminosity scale of early- and mid-type T dwarfs would provide much improved mass and age constraints for this system.

Through determination of its orbital inclination and better constraints on the component luminosities, 2MASS J0320−0446 has the potential to provide absolute tests of brown dwarf evolutionary models at late ages, regardless of their current relative agreement. This source may not be the only useful one for such empirical constraints, however. As discussed in Bu08, 1-5% of all M8–L0 dwarf systems should have component spectral types that can be determined via the method outlined in Burgasser (2007b), and some fraction of these (perhaps as many as 50%; Maxted & Jeffries 2005) will also be spectroscopic binaries. A concerted follow-up effort of such systems will allow critical assessment of current theoretical understanding of brown dwarf interiors and evolution, addressing uncertainties in low-temperature hydrogen fusion, interior thermal transport (including the influence of conduction in the most massive brown dwarf cores; Chabrier et al. 2000) and substellar interior structure.

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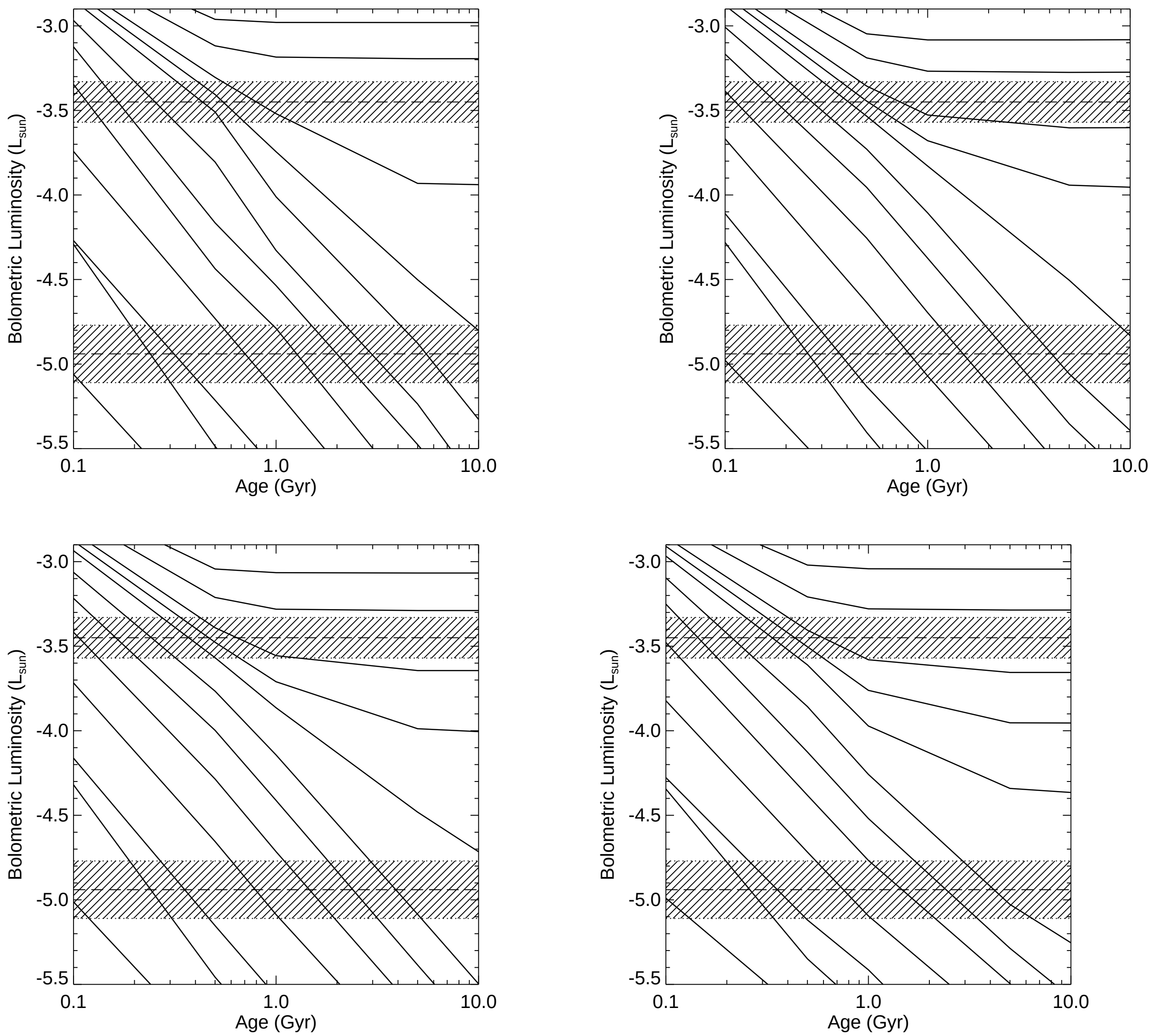

Fig. 1.— Luminosity evolutionary tracks based on models from Burrows et al. (1997, 2001, upper left); Baraffe et al. (2003, upper right); and Saumon & Marley (2008, bottom left: cloudless; bottom right: cloudy). Tracks are shown for masses of 0.01, 0.015, 0.02, 0.03, 0.04, 0.05, 0.06, 0.07, 0.075, 0.08, 0.09, and 0.1 $M_{\odot}$, from lower left to upper right in each panel. The estimated luminosities and uncertainties of the two components of 2MASS J0320−0446 are indicated by the hatched regions.

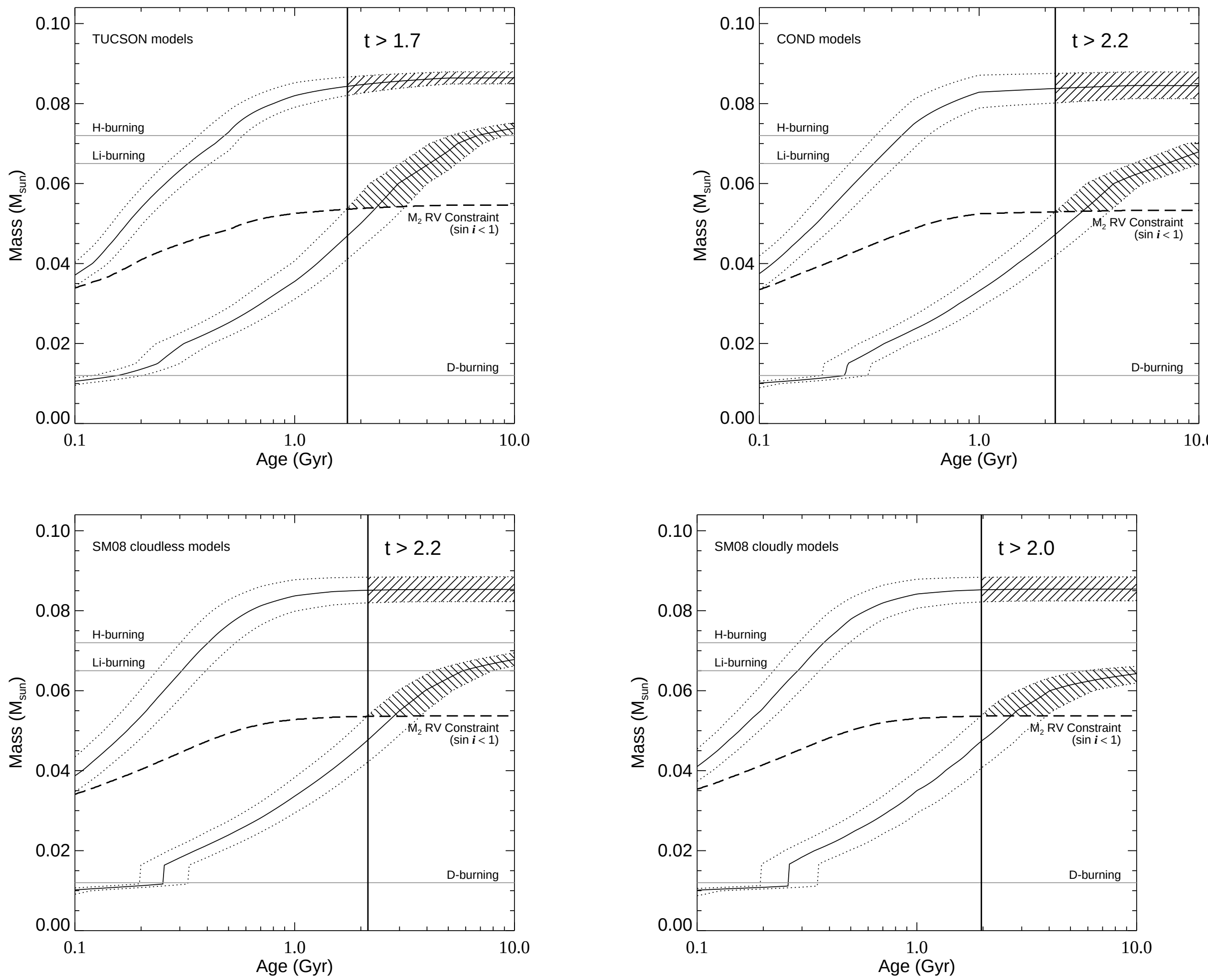

Fig. 2.— 2MASS J0320−0446 component masses (solid lines; dotted lines indicate uncertainty range) as a function of age based on the component luminosity constraints shown in Figure 1. Age-dependent constraints on the minimum secondary mass based on the primary radial velocity orbit and lower bound of the primary mass, and assuming $\sin i \leq 1$, are indicated by dashed lines. The intersection of this line with secondary component mass constraints based on its luminosity sets the minimum age of the 2MASS J0320−0446 system, 1.7–2.2 Gyr. The hatched regions indicate parameter spaces allowed by the luminosity and radial velocity measurements and evolutionary models Horizontal grey lines indicate threshold masses for core hydrogen (0.075 $M_{\odot}$), lithium (0.065 $M_{\odot}$) and deuterium fusion (0.013 $M_{\odot}$), assuming solar metallicity.

Table 1. Mass and Age Constraints for the 2MASS J03202839−0446358 System.

Parameter	TUCSON cloudless	COND cloudless	SM08 cloudless	SM08 cloudy
Minimum age (Gyr)	1.7	2.2	2.2	2.0
Minimum $\sin i$[a]	0.80 (53°)	0.82 (55°)	0.83 (56°)	0.86 (59°)
M_1 ($M_\odot$)[a]	0.082–0.088	0.080–0.088	0.082–0.088	0.082–0.088
M_2 ($M_\odot$)[a]	0.054–0.075	0.053–0.070	0.054–0.069	0.054–0.066
M_2/M_1	0.62–0.89	0.60–0.87	0.61–0.84	0.61–0.80
Age for $\sin i = 1$ (Gyr)	$2.5^{+1.0}_{-0.7}$	$3.2^{+1.3}_{-0.9}$	$3.0^{+1.2}_{-0.8}$	$2.8^{+1.7}_{-0.9}$

[a]Minimum $\sin i$ and maximum masses and mass ratios assume that the age of 2MASS J0320−0446 is less than 10 Gyr.