

# Confronting substellar theoretical models with stellar ages

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**Abstract.** By definition, brown dwarfs never reach the main-sequence, cooling and dimming over their entire lifetime, thus making substellar models challenging to test because of the strong dependence on age. Currently, most brown dwarfs with independently determined ages are companions to nearby stars, so stellar ages are at the heart of the effort to test substellar models. However, these models are only *fully* constrained if both the mass and age are known. We have used the Keck adaptive optics system to monitor the orbit of HD 130948BC, a brown dwarf binary that is a companion to the young solar analog HD 130948A. The total dynamical mass of  $0.109 \pm 0.003 M_{\odot}$  is the most precise mass measurement (3%) for any brown dwarf binary to date and shows that both components are substellar for any plausible mass ratio. The ensemble of available age indicators from the primary star suggests an age comparable to the Hyades, with the most precise age being  $0.79^{+0.22}_{-0.15}$  Gyr based on gyrochronology. Therefore, HD 130948BC is unique among field L and T dwarfs as it possesses a well-determined mass, luminosity, and age. Our results indicate that substellar evolutionary models may underpredict the luminosity of brown dwarfs by as much as a factor of  $\approx 2-3\times$ . The implications of such a systematic error in evolutionary models would be far-reaching, for example, affecting determinations of the initial mass function and predictions of the radii of extrasolar gas-giant planets. This result is largely based on the reliability of stellar age estimates, and the case study of HD 130948A highlights the difficulties in determining the age of an arbitrary field star, even with the most up-to-date chromospheric activity and gyrochronology relations. In order to better assess the potential systematic errors present in substellar models, more refined age estimates for HD 130948A and other stars with binary brown dwarf companions (e.g.,  $\epsilon$  Ind Bab) are critically needed.

**Keywords.** stars: brown dwarfs; techniques: high angular resolution; binaries: close, visual; infrared: stars

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## 1. Introduction

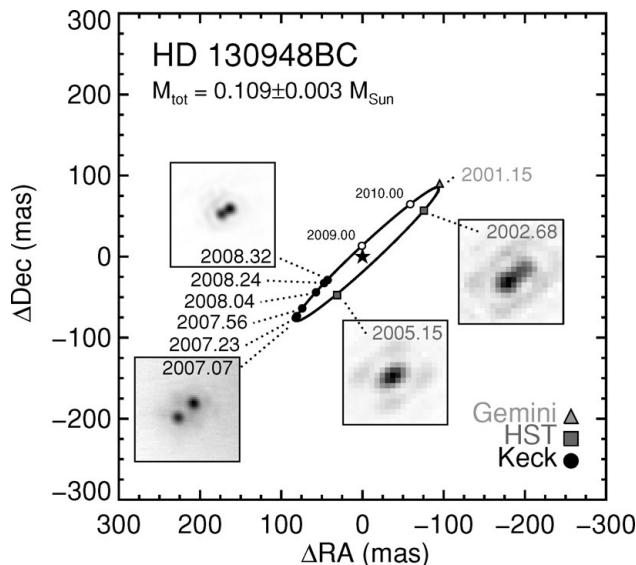
Theoretical models of objects below the substellar limit ( $M < 0.075 M_{\odot}$ ) are essential for characterizing the several hundred brown dwarfs and extrasolar gas-giant planets discovered to date. Thus, these models have become ubiquitous in the literature, even though empirical tests of their ability to accurately predict the properties of brown dwarfs has been limited to only a handful of relatively warm objects. To test substellar evolutionary models, the input parameters of mass and age must be determined. For young brown dwarfs, the M6.5 eclipsing binary 2MASS J05352184–0546085 in the Orion Nebula provides a unique benchmark (Stassun *et al.* 2006). Prior to this year, only three binaries provided dynamical mass measurements for field objects at or below the substellar limit: the M8.5 + M9 binary LHS 1070BC (Leinert *et al.* 2001; Seifahrt *et al.* 2008); the M8.5 + M9 binary Gl 569Bab (Zapatero Osorio *et al.* 2004; Simon *et al.* 2006); and the L0.5 + L1 binary 2MASS J0746 + 2000AB (Bouy *et al.* 2004). Recent work

has contributed several more dynamical masses for objects lower in both temperature and mass than previously studied: the mid-L dwarf GJ 802B (Ireland *et al.* 2008); the T5 + T5.5 dwarf binary 2MASS J1534-2952AB (Liu *et al.* 2008); and the L4 + L4 binary HD 130948BC (Dupuy *et al.* 2008). While mass measurements alone can provide very stringent tests of theoretical models (e.g., see Liu *et al.* 2008), substellar evolutionary models are only fully constrained when both the mass and age can be determined. In fact, precise ages are critical for such tests because brown dwarfs – unlike stars – never reach a main-sequence, so their properties depend very sensitively on their age.

Of the substellar field dwarfs with measured masses, only HD 130948BC has a precisely determined age. These nearly-identical L dwarfs were discovered by Potter *et al.* (2002) as companions to the young solar analog HD 130948A (G2V,  $[Fe/H] = 0.05$ ). *Hipparcos* measured a distance of  $18.17 \pm 0.11$  pc (van Leeuwen 2007) for the primary star, which enables a very precise dynamical mass measurement when paired with our well-determined orbital solution.

## 2. The mass of HD 130948BC

We have used Keck adaptive optics (AO) imaging to monitor the relative orbit of the two components of HD 130948BC (Figure 1). Combined with archival *Hubble Space Telescope* (*HST*) imaging and a re-analysis of the Gemini discovery data, our data span  $\approx 7$  years ( $\approx 70\%$  of the orbital period). We fit a simple analytic PSF model to derive astrometry from the Keck and Gemini images, while TinyTim model PSFs were fit to the *HST* images. An individually tailored Monte Carlo simulation was used to determine the astrometric uncertainty for each observation epoch. The resulting astrometry is extremely precise with typical Keck errors of  $300 \mu\text{as}$ , corresponding to  $\approx 1 R_{\odot}$  at the distance of this system, while the orbit is roughly the size of the asteroid belt. We determined the binary's orbital parameters and their confidence limits using a Markov Chain Monte Carlo



**Figure 1.** Keck (circles), *HST* (squares), and Gemini (triangle) relative astrometry for HD 130948BC along with the best-fit orbit. Error bars are smaller than the plotting symbols. The empty circles are the predicted positions in 2009 and 2010.

(MCMC) technique. The best-fit orbit has a reduced  $\chi^2$  of 1.06 (9 degrees-of-freedom), thus validating our astrometric error estimates. Applying Kepler's Law to the MCMC-derived orbital period ( $P = 9.9_{-0.6}^{+0.7}$  yr) and semimajor axis ( $a = 121 \pm 6$  mas) yields a dynamical mass of  $0.1089_{-0.0017}^{+0.0020} M_{\odot}$ . Accounting for the additional uncertainty in the *Hipparcos* distance results in a dynamical mass of  $0.109 \pm 0.003 M_{\odot}$  ( $114 \pm 3 M_{\text{Jup}}$ ).

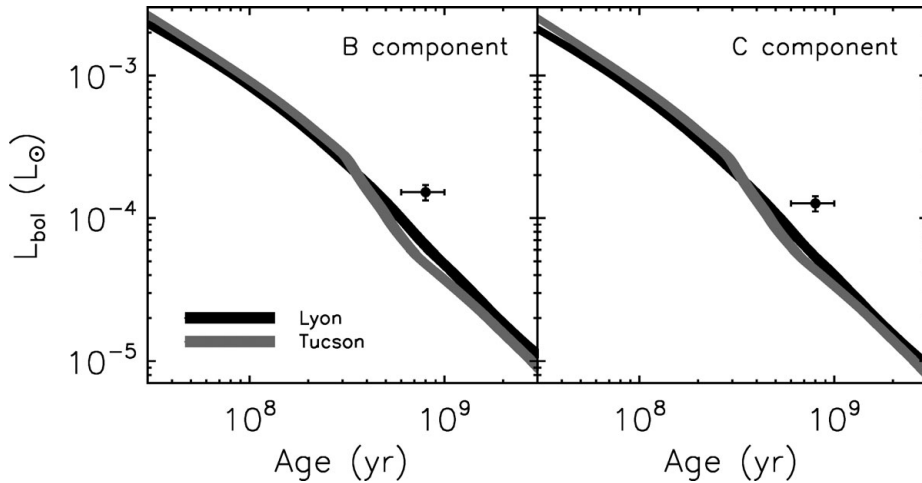
In the following analysis, we apportion the total mass between the two components by converting the measured luminosity ratio into a mass ratio using evolutionary models. The resulting individual masses are very insensitive to the models used because the flux ratio is so close to unity (the steepness of the mass–luminosity relation means that even small differences in mass result in large differences in luminosity). Regardless, we are careful to conduct our analysis in a self-consistent manner free of circular logic.

### 3. The age of HD 130948A

As a young solar analog, multiple indicators are available to assess the age of HD 130948A:

- *Rotation/Gyrochronology* — Gaidos *et al.* (2000) measured two rotation periods of 7.69 and 7.99 days for HD 130948A. Thus, we adopt a rotation period of  $7.84 \pm 0.21$  days and a  $B - V$  color of  $0.576 \pm 0.016$  mag from the *Hipparcos* catalog. We employ the Mamajek & Hillenbrand (2008) calibration of the “gyrochronology” relation originally introduced by Barnes (2007). The age we derive is  $0.79_{-0.15}^{+0.22}$  Gyr, where the confidence limits are determined through a Monte Carlo approach in which the period, color, and empirical coefficients are drawn from normal distributions corresponding to their uncertainties.
- *Chromospheric Activity* — Henry *et al.* (1996) and Wright *et al.* (2004) measure  $\log(R'_{HK})$  values of  $-4.45$  and  $-4.50$  for HD 130948A, respectively. Using the activity–age relation of Mamajek & Hillenbrand (2008), we derive ages of 0.4 and 0.6 Gyr from these  $\log(R'_{HK})$  values. The empirical relation is expected to give ages with an uncertainty of  $\approx 0.25$  dex, so we adopt a mean age of  $0.5 \pm 0.3$  Gyr from this method.
- *X-ray Activity* — HD 130948A was detected by *ROSAT*, and Hüensch *et al.* (1999) measure  $\log(L_X) = 29.01$  dex (cgs), which gives  $\log(R_X) = -4.70$ . Using the empirical relation of Gaidos (1998), this corresponds to an age of 0.1–0.3 Gyr, depending on whether we adopt  $\alpha$  of 0.5 or  $1/\exp$ . The X-ray relation of Mamajek & Hillenbrand (2008), derived by combining their  $\log(R_X)$ – $\log(R'_{HK})$  and  $\log(R'_{HK})$ –age relations, gives an age of 0.5 Gyr. The X-ray luminosity of HD 130948A is in agreement with single G stars in the Pleiades and Hyades (28.9–29.0; Stern *et al.* (1995); Stelzer & Neuhäuser (2001)).
- *Isochrones* — Using high resolution spectroscopic data combined with a bolometric luminosity and model isochrones, Valenti & Fischer (2005) derived an age estimate of 1.8 Gyr, with a possible age range of 0.4–3.2 Gyr. From the same data and with more detailed analysis, Takeda *et al.* (2007) found a median age of 0.72 Gyr, with a 95% confidence range of 0.32–2.48 Gyr.
- *Lithium* — Measurements by Duncan (1981), Hobbs (1985), and Chen *et al.* (2001) give lithium equivalent widths of  $95 \pm 14$ ,  $96 \pm 3$ , and  $103 \pm 3$  mÅ, respectively, for HD 130948A. Compared to stars of similar color, these values are slightly lower than the mean for the Pleiades and slightly higher than for UMa and the Hyades, though consistent with the scatter in each cluster's measurements Soderblom *et al.* (1993a,b,c)

In summary, the most precise age estimate available for HD 130948A comes from gyrochronology, which gives an age of  $0.79_{-0.15}^{+0.22}$  Gyr. All other age indicators agree with this estimate, though this is due to their large uncertainties rather than a true consensus.



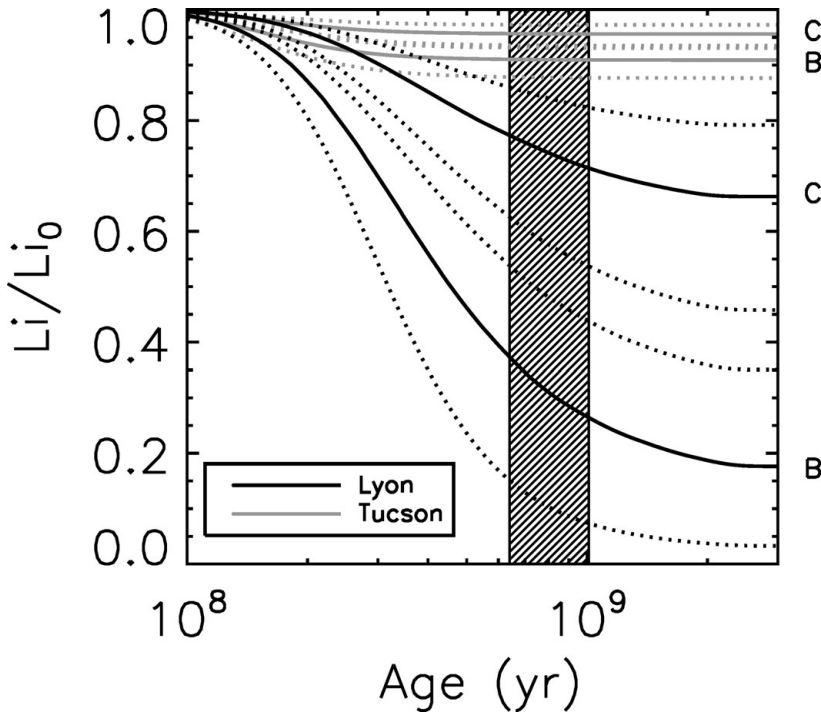
**Figure 2.** The filled circles mark the measured luminosities of HD 130948B and C at the age we derive for HD 130948A. The thick shaded lines are isomass lines from evolutionary models, where the line thicknesses encompass the  $1\sigma$  errors in the individual masses of HD 130948BC. Although the two independent sets of models agree very well with one another, they underpredict the luminosities of HD 130948BC by a factor of  $\approx 2\text{--}3\times$ .

#### 4. Substellar evolutionary models fully constrained

With a measured mass, luminosity, and age, HD 130948BC provides the first direct test of the luminosity evolution predicted by theoretical models for substellar field dwarfs. Both the Tucson models (Burrows *et al.* 1997) and Lyon models (DUSTY; Chabrier *et al.* 2000) underpredict the luminosities of HD 130948B and C given their masses and age. The discrepancy is quite large, about a factor of 2 for the Lyon models and a factor of 3 for the Tucson models (Figure 2). If the age and luminosities of HD 130948B and C had been used to infer their masses, the resulting estimates would have been too large by 20–30%. In order to explain this discrepancy entirely, model radii would have to be underpredicted by 30–40%. Alternatively, the age of HD 130948A would need to be  $\approx 0.4$  Gyr in order to resolve this discrepancy. Although such a young age is marginally consistent with the various age indicators; it is on the extreme young end of two independent, well-calibrated age estimates (gyrochronology and stellar isochrones). In order to better assess this discrepancy between models and data, a more refined age estimate for HD 130948A (e.g., from asteroseismology) is critically needed.

#### 5. Lithium depletion in HD 130948BC

Since brown dwarfs are fully convective objects, they can rapidly deplete their initial lithium if their core temperature is ever high enough to do so. This threshold is reached around  $0.065 M_{\odot}$ , and since this is below the hydrogen-burning mass-limit, this fact has been exploited to identify sufficiently old objects bearing lithium as substellar. In fact, the exact mass-limit for lithium burning is slightly different depending on which sets of theoretical models are used, and the masses of HD 130948B and C happen to be very close to these theoretically predicted mass-limits (Figure 3). According to the Tucson models, neither component is massive enough to have ever depleted a significant amount of its initial lithium. The Lyon models, on the other hand, predict that HD 130948B is massive enough to have depleted most of its lithium, while HD 130948C is not. Thus, resolved optical spectroscopy designed to detect the lithium doublet at  $6708 \text{ \AA}$  would provide a



**Figure 3.** Lithium depletion as a function of age as predicted by evolutionary models. The solid lines correspond to the individual masses of HD 130948B and C. These lines are bracketed by dotted lines that correspond to the  $1\sigma$  uncertainties in the individual masses. The ordinate is the fraction of initial lithium remaining. The hatched black box indicates the constraint from the age of HD 130948A estimated from gyrochronology.

very discriminating test of substellar evolutionary models, which are otherwise nearly indistinguishable (e.g., see Figure 2). This experiment can currently only be conducted with *HST*/STIS given the very small binary separation ( $< 130$  mas).

## 6. Future prospects

Brown dwarfs hold the potential to address many astrophysical problems. For example, they are excellent laboratories in which to study ultracool atmospheres under a variety of conditions, and they may eventually be useful as Galactic chronometers given how sensitively their properties depend on their age (see contribution by A. Burgasser). However, the theoretical models we rely upon to characterize brown dwarfs have only begun to be rigorously tested by benchmark systems such as HD 130948BC. More results are expected to be forthcoming over the next several years for other brown dwarf binaries with stellar companions:  $\epsilon$  Ind Bab (McCaughrean *et al.* 2004); GJ 417BC (Bouy *et al.* 2003); and GJ 1001BC (Golimowski *et al.* 2004). However, the utility of these systems as benchmarks critically depends on the confidence in the age estimates for their primary stars. Therefore, these stars deserve special attention so that state-of-the-art age-dating techniques (e.g., asteroseismology and gyrochronology) may be applied to them. Also, extending the empirical relations between age, stellar rotation, and chromospheric activity to include objects with as late a spectral type as possible will enable many more systems to be used as benchmarks for testing models. These relations are currently only

calibrated for stars as late as early-K, but about half of the stars with brown dwarf companions have spectral types between early-K and early-M.

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## Discussion

F. WALTER: It is always risky to attempt to pin down the age of a field star, even using multiple techniques that may agree. How much would the age have to be changed to place the L dwarfs on the proper evolutionary tracks?

T. DUPUY: I agree and would really like to see another independent measurement of the age, such as from asteroseismology. The age of the system would have to be about 0.4 Gyr to bring the models into agreement with the data.

E. JENSEN: Is there a measured metallicity for HD 130948A? The metallicity will affect the evolutionary models, both in the HR diagram and for Li depletion.

T. DUPUY: That's exactly right and is a detail I didn't go into. The metallicity of HD 130948A is basically solar, which means we can use the standard models. This is another reason why having brown dwarfs with stellar companions is great: you can make sure you're not being confused by metallicity effects like Adam talked about.

A. WEST: Does the fact that this system is a close binary affect the measured luminosity (because the radii are affected)?

T. DUPUY: The binary separation is about 2.2 AU, so it's unlikely that tidal effects are at work in this system. Also, it turns out that the two components receive about as much flux from each other as they do from the primary star, so irradiation shouldn't be affecting them much.

J. FERNANDEZ: The next main source of benchmarks for brown dwarfs will be Kepler and Corot. The precise determination of ages for the primary stars will be crucial.



Sydney Barnes