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Age determination for Ultracool Dwarfs

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Abstract. Brown dwarfs are notoriously difficult to age date as they lack stable hydrogen burning hence main-sequence star age-dating techniques are inapplicable for their masses. However precise and accurate ages for individual sources are required to determine masses and disentangle how secondary parameters such as differing metallicity, cloud structure and gravity impact observables. In this contribution, I review age-dating techniques for brown dwarfs as well as "piggy-back" techniques that rely on co-moving, higher mass, main-sequence stars for which Gaia may substantially increase the sample.

Key words. Stars: brown dwarfs – Stars: kinematics and dynamics – Stars: late-type – Stars: low-mass – Galaxy: kinematics and dynamics

1. Introduction

With masses intermediate between stars and planets, brown dwarfs provide a natural link between stellar astrophysics and the planetary science of gas-giants. They form in the same manner as stars but lack enough mass to trigger sustained nuclear burning (Kumar 1962, Hayashi & Nakano 1963). This leads to a degeneracy between temperature and observables and an important overlap with the measurable properties of the lowest mass stars and the highest mass planets.

Determining the difference between a main-sequence star that is stably burning hydrogen and a brown dwarf of lower mass incapable of such stable fusion is not always straightforward (see overlap in Figure 1). Furthermore, determining the difference between a deuterium burning brown dwarf and one that never has a core temperature high enough to ignite even heavy hydrogen (a planet) is equally difficult.

Determining masses directly is the ideal approach to breaking the age-mass degeneracy but this is not possible for the majority of the brown dwarf population (see section 2.5). Therefore ages become the critical observable to understanding the physical properties of brown dwarfs. In this proceeding I review the major methods employed to age-date low-mass, low-temperature sources (encompassing stars, brown dwarfs, and planets) and reflect on how Gaia will contribute moving forward.

2. Summary of age-dating techniques for ultracool dwarfs

Brown dwarfs are classified using red optical or near-infrared spectra and show characteristics which distinguish them as M,L (T_{eff} ~3000 - 1300K) or T,Y (T_{eff} <1300) dwarfs (Kirkpatrick et al. 1999; Burgasser et al. 2002; Cushing et al. 2011). At each spectral type, there may be an indistinguishable mix of

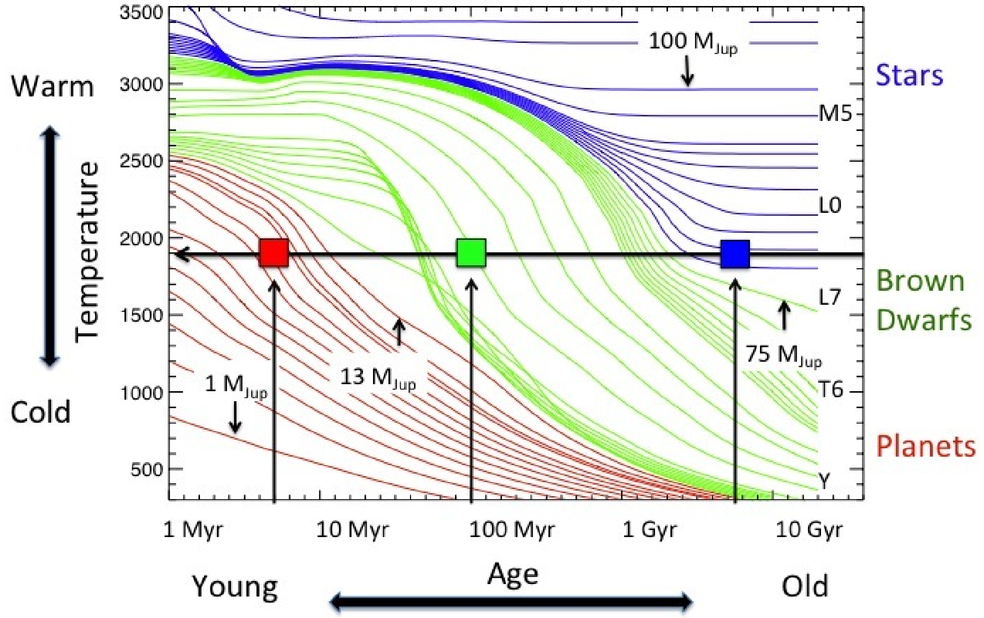

Fig. 1. The evolutionary diagram from the Burrows et al. (1997) models for low-mass stars (blue), brown dwarfs (green), and planets (red) demonstrating the degeneracy between age and mass. Highlighted by the left-right arrow marking ~1700K are three equivalent T_{eff} objects: a 7 Myr, 9 M_{Jup} planet (red-left), a 90 Myr, ~30 $_{Jup}$ brown dwarf (green-center), and an 8 Gyr, 80 $_{Jup}$ low-mass star (blue-right). As they are the same T_{eff} all three would share observable properties.

brown dwarfs, low-mass stars or free-floating planets (see Figure 1). Consequently, for the purposes of this review, I refer to the population in question as ultracool dwarfs (UCDs) since this general team is more true to all classes of objects potentially included in the analysis.

The age-dating techniques for UCDs can be broadly summarized as falling in four categories:

2.1. Li I *absorption studies*

The core temperature required to ignite lithium burning is lower than that required for hydrogen burning. In turn, this translates into a lower fusing mass limit (~ 0.065 $M_{\odot}$; Rebolo et al. 1992, Magazzu et al. 1993). The interiors of lower mass stars and brown dwarfs are fully convective, therefore objects above this fusing mass limit will fully deplete their reservoir of lithium (in ~ << 1 Gyr; e.g. Chabrier et al. 1996) while those below it, will not. Consequently, a detection of lithium in UCDs (T_{eff} < ~ 2700; Basri 1998) implies a mass limit of ~0.065 $M_{\odot}$ which can be translated into an age upper limit using an effective temperature (T_{eff}) estimate and evolutionary models.

At present there is a selection of ~ 100 field-age (1 - 5 Gyr) brown dwarfs with Li I absorption measurements that can be used to determine trends with this important feature. According to Kirkpatrick et al. (2008), Li I absorption rises through mid-type L dwarfs before decreasing in strength with decreasing T_{eff}. At T_{eff} < 1500 K , Li is largely condensed into molecules of LiCl, LiF therefore little to none is seen as 6708 Å Li I absorption.

The first T dwarf with a Li I detection was only recently reported by Faherty et al. (2014).

As stated in Kirkpatrick et al. 2008, there is evidence indicating that the Li I line weakens markedly for the youngest ages. Similar to how the Na I and K I alkali lines weaken for < 150 Myr brown dwarfs (see section 2.1), it is thought that gravity effects also impact the Li I line. At present there is not a significant sample of independently age-calibrated brown dwarfs to test the extent of this effect – although this is rapidly changing with the characterization of sources such as 2M0355; Faherty et al. (2013b), W0047; Gizis et al. (2012), and PSO318; Liu et al. (2013).

2.2. Surface gravity indications

As depicted in Figure 1, a young giant exoplanet and an older brown dwarf or low-mass star can share the same T_{eff}. The major difference in the observables arises because younger sources have a lower surface gravity hence significantly different pressure ($P \sim g/k_R$, where k_R is the Rosseland mean opacity). Observationally, this alters data in the form of weak collision-induced H_2 absorption, a sharply peaked H band spectrum, weakened alkali lines, and enhanced metal-oxide absorption bands (e.g. Lucas et al. 2001; Gorlova et al. 2003; Luhman et al. 2004; McGovern et al. 2004; Allers et al. 2007; Rice et al. 2010, 2011; Cruz et al. 2009).

At present there are two classification systems for designating a source as low-surface gravity by its spectral features. The Cruz et al. (2009) system which examines the optical data and assigns a low-surface gravity (γ), intermediate gravity (β), or field gravity based on the strength of metal oxide absorption bands and alkali lines. On the Cruz et al. (2009) scheme, γ and β objects are thought to be younger than Pleiades age stars (age $< \sim$ 100 - 150 Myr). There is also the Allers & Liu (2013) system, which examines near-infrared spectral data and uses spectral indices to assign a very low gravity (vl-g), intermediate gravity (int-g), or field gravity (fld-g) to a given source. Overall, the two systems are consistent; however, both require an age-calibrated sample to ground the gravity designations as age-indicators.

2MASS J035523.51+113337.4 (2M0355), is a signature low surface gravity L dwarf and it was discussed in detail by Faherty et al. (2013b). Its optical spectrum exhibits strong bands of VO but abnormally weak TiO, K I, and Na I absorption (Cruz et al. 2009). In the near-infrared, its red $J - K$ color (2MASS $J - K_s$=2.52) and triangular H-band spectral morphology distinguish it from field L dwarfs (Faherty et al. 2013b, Allers & Liu 2013). It is a confirmed member of the 150 Myr AB Doradus moving group (Faherty et al. 2013b, Liu et al. 2013, Gagné et al. 2013). Since the discovery and characterization of 2M0355, many other L dwarfs showing similar spectral and photometric variations have been postulated as members of nearby moving groups (e.g. Gagné et al. 2013, Faherty et al. 2013). These sources will become the anchor for grounding the gravity designations as age-indicators. Furthermore, Gaia will revolutionize our understanding of nearby moving groups. For those sources that cannot be fit into the current collection of young associations, Gaia may very well reveal new ones which they do fit into, perhaps compromised solely of UCDs (see **?** and Malo et al. 2014).

2.3. Chromospheric activity

For the warmest UCDs – in general the M dwarfs – magnetic activity plays an important role. In solar-type stars, magnetic field generation is linked to rotation periods which has been shown to slow with time. Logically, activity level can also be linked to age. Skumanich (1972) was among the first to demonstrate this by measuring Ca II emission for main sequence stars in tandem with rotation and found that both decrease over time as a power law ($t^{-0.5}$). Many studies have found evidence that this same age-activity relation applies through the UCD regime (e.g Eggen 1990, Gizis et al. 2002).

The key tracer for activity among UCDs is Hα equivalent widths (see Schmidt et al. 2014), M dwarf activity increases with decreasing temperature through M7 dwarfs where, for the most part, all nearby objects show Hα activity. However, it is not clear that this trend continues at the cooler temperatures of M8 dwarfs and beyond where the photospheres become increasingly neutral (Mohanty et al. 2002; Gelino et al. 2002). West et al. (2008) suggest activity lifetimes for M0-M7 dwarfs based on Hα equivalent width and vertical distance from the Galactic Disk Plane.

2.4. Kinematics

While individual space motions can not be used to date objects, general information can be obtained from UVW velocity distribution. The most reliable usage of UVW velocities for age studies is searching for new members of well-studied moving groups with relatively small velocity dispersions – < 1 km s^{-1} – (e.g. β Pictoris ~ 20 Myr, AB Doradus ~ 150 Myr, Tucana Horologium ~ 30 Myr, TW Hydrae ~ 20 Myr; see Riedel et al. 2014). The Hipparcos dataset uncovered the kinematic structure of many of the known, nearby young associations. With its superior astrometry and additional radial velocity data, Gaia is expected to revolutionize our understanding of the kinematic structure of the Milky Way uncovering hidden groups, some of which may very well be primarily compromised of low mass stars and UCD's.

For the current UCD population, parallaxes and proper motions are now in relatively large supply but radial velocity measurements are sparse. Using convergent point or bayesian inference methods one can minimize the significance of the missing kinematic measurement and determine a probability of membership in nearby moving groups (see Riedel et al. 2014 and Malo et al. 2014). Coupled with spectral or photometric gravity signatures as evidence for youth, one can piggy-back on the age diagnostics of the higher mass stars in the associations, assume co-evality, and retain the well-constrained age of the group for the individual object (e.g. Faherty et al. 2013, Gagné et al. 2013).

To a lesser extent, overall population kinematics can be used to determine ages (e.g. Seifahrt et al. 2010, Zapatero Osorio et al. 2007, Faherty et al. 2009). As shown in several large scale kinematic studies, a comparison of the total velocity dispersion for nearby stellar populations can be an indicator of age as the random motions of a population of disk stars are known to increase with time. This effect is known as the disk age-velocity relation (AVR) and is simulated by fitting well-constrained data against the following analytic form:

$$\sigma(t) = \sigma_0(1 + \frac{t}{\tau})^{\alpha} \tag{1}$$

where $\sigma(t)$ is the total velocity dispersion as a function of time, σ_0 is the initial velocity dispersion at t=0, τ is a constant with unit of time, and α is the heating index (Wielen 1977). $\sigma(t)$ is defined for U,V,W space velocities but several groups have estimated the total velocity dispersion of the UCD population using measured tangential velocities (e.g. Schmidt et al. 2007, Faherty et al. 2009, Gizis et al. 2000). At present there is some conflict as to the kinematic age of the population with groups claiming anywhere from 3 - 5 Gyr. What is clear, is that there are subpopulations with deviant kinematics (Faherty et al. 2009). When near-infrared color is included in the analysis, one finds that sources that are bluer/redder for their subtype have larger/smaller velocity dispersions hence concluded to be older/younger (Faherty et al. 2009, Schmidt et al. 2010).

2.5. Dynamical mass measurements

One of the main methods for addressing the age of a brown dwarf and breaking the age-mass degeneracy is to measure the mass of an object directly. Dynamical mass measurements are possible for a small subset of the brown dwarf population found in sufficiently tight binaries (e.g. Zapatero Osorio et al. 2004, Liu et al. 2008, Konopacky et al. 2010, Dupuy et al. 2009b,c,a, 2010). For suitable cases one can monitor the binaries orbit using astrometric images (adaptive optics) or radial velocity measurements and calculate a period and semi-major axis, apply Kepler's law and obtain the total mass of a system. Subsequently, relative photometry or recoil motion can be used to determine individual component masses. Optimally, the system has a well determined distance so the uncertainty in all measured orbital parameters is minimized. With component luminosities and masses in hand, evolutionary models are applied and the system age is estimated.

In an ideal case, the brown dwarf binary is found as a widely separated system from a well-studied main sequence star (as is the case for systems such as HD130948BC Dupuy et al. 2009b and Gl 417BC Dupuy et al. 2014) therefore one has a secondary check on the resultant age of the system.

Of the ~ 100 very low mass (M_{tot} < 0.1 $M_{\odot}$) binaries, only a small percentage have sufficiently short periods that such dynamical mass measurements are possible. In the literature there are upward of 15 brown dwarf systems with masses directly measured, less than a handful of which are found orbiting well-studied main sequence stars so they have a secondary check on their age. Among the latter sample, Dupuy et al. (2009b) and Konopacky et al. (2010) found that substellar evolutionary models may under predict the luminosity of brown dwarfs by as much as a factor of ~ 2 - 3. Consequently, even with direct mass measurements, there is an underlying uncertainty that comes with using the evolutionary models to determine an age.

2.6. Benchmarks

One useful group of UCD benchmarks are those which are resolved companions to nearby, well-characterized stars. Exploiting kinematics (proper motion, parallax and radial velocity where available) for both the main-sequence star and the UCD, co-moving companions can be uncovered and co-evality assumed. As there are far more age-dating techniques available for stars (e.g. Li depletion, theoretical isochrones, chromospheric activity, gyrochronology, see summaries in Mamajek et al. 2009), there is a much better chance of getting a well defined age by associating a brown dwarf with a main sequence star. Unfortunately, the current population of UCD companions is sparse with less than fifty M8 or later wide (> 100 au) co-moving systems (e.g. Gizis et al. 2001, Lafrenière et al. 2008, Faherty et al. 2010, 2011, Burningham et al. 2013, Gomes et al. 2013, Mužić et al. 2012). Burningham et al. (2013) and Gomes et al. (2013) place a minimum value of 5 - 8% on the wide binary companion fraction of L - T dwarfs therefore, thousands of systems are likely waiting to be discovered (see Kirkpatrick 2014).

3. Ultracool dwarf ages in the era of Gaia

Given the small number of field brown dwarf astrometric detections expected from Gaia, the mission will not directly impact age studies. However, indirectly, Gaia will have a major effect on our understanding of brown dwarf ages. Gaia will provide kinematics for nearby main-sequence stars that can be used in complimentary brown dwarf studies to uncover nearby co-moving companions. Gaia will redefine nearby moving groups which contain brown dwarfs that need to have surface gravity observables calibrated. In the rare case where Gaia can directly impact, Sarro et al. (2014) predicts Gaia may observe brown dwarfs in nearby star forming regions such as Orion, Rho Ophiucus, the Pleiades and the Hyades, providing age-calibrated mass functions well into the brown dwarf regime.

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