The Discovery of the First Lithium Brown Dwarf: PPl 15

Gibor Basri

Abstract The search for brown dwarfs (BDs) covered decades between the time they were first proposed theoretically and the time that a public announcement of the discovery of a BD was made which did not have to be recanted later (as was the case for a number of previous announcements). In a convergence of scientific progress, 1995 saw 3 real discoveries of BDs, as well as the first exoplanets. The substellar realm had suddenly opened up. This chapter describes the process that led to the first of these announcements: the identification of PPl 15 as a BD. It lay just below the substellar limit in the Pleiades cluster. To distinguish it from very similar-looking stars, the first successful application of the "lithium test" was applied by my group at UC Berkeley using the new Keck 10-m telescope and HIRES spectrograph. As part of the analysis, the new technique of "lithium dating" was developed. I place this discovery in the context of the broader search for BDs, and of the subsequent discoveries and progress in the field.

1 Introduction: Search Techniques for Brown Dwarfs

The search for BDs was a long and frustrating process, if measured from the time that they were first posited theoretically [Kumar 1963]. It was known from the outset that BDs would start off rather faint and cool, and by their very substellar nature, grow continuously fainter and cooler with time. This imposes several observational constraints on search techniques. One is that the search should be conducted as redward as possible in the optical band, or even better, at near infrared wavelengths. The technology to do this efficiently did not really come into its own until the 1990s. Red sensitivities of photographic film were not high, and CCDs were only introduced in the previous decade. Most BDs lay beyond the sensitivity of older surveys like the

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Palomar Sky Survey because of their faintness and extremely red colors. Even cooler M stars were very sparsely known. Infrared detectors did not have many pixels until then, meaning that angular coverage was extremely limited.

The alternate approach is to search for BDs when they are very young, which means they will be at their brightest and warmest. Indeed, very young BDs actually have the M spectral class (and it turned out later that some long known nearby M stars are actually BDs). The problem in this case is finding a way to distinguish between objects of M spectral class that are true stars from those that are substellar. The obvious thing to do is find them in binaries in which a mass determination can be made from the orbit. Unless it is an eclipsing system, however, one cannot be sure whether the inclination is small enough to cause what is actually a star to appear to have an apparently substellar mass. The other approach is to find a nuclear diagnostic that proves that the object has not undergone nuclear burning under conditions only a true star can achieve. Such a diagnostic was proposed by [Rebolo et al. 1992], and it is the first successful use of that lithium test that is the primary subject of this chapter. The first true discoveries of single BDs were announced in 1995 in June and September utilizing the lithium test; they are the subject of this chapter and the one by Rebolo in this volume. Extensive reviews of early observational efforts (up through the first set of successful ones) can be found in [Oppenheimer et al. 2000] and [Basri 2000]. I next provide a brief general summary of the early campaigns to find BDs.

1.1 Brown Dwarfs as Companions to Stars

If one does not know where to look for BDs, an excellent place to start is near to a star. We know that the binary fraction of stars is high, ranging from 75% or more around high mass stars to about 25% around low mass stars [Duchêne & Kraus 2013]. Although it was not clear how that applies to BDs, one does not need much angular coverage to look for companions to stars. Instead the problem is one of angular resolution, which in turn drives one to study nearby systems. One unfortunate side effect of such a search is that the typical system will be rather old, and the BD keeps fading away while its stellar companion does not. This acts as another strong driver to study nearby systems. Both the angular separation and contrast ratio will produce a detection bias for systems with large separations. It is also possible to search for BDs through the radial velocity variability they would produce on their stellar companion. This has the great advantage that the faintness of the BD is irrelevant, but it is strongly biased to detect close companions.

One of the first efforts to directly image BDs as companions to nearby stars was made by [McCarthy et al. 1985]. Using an infrared speckle technique, they reported a companion to VB8, with inferred properties that would guarantee its substellar status. This was the highlight of the first conference on BDs [Kafatos et al. 1986]. Unfortunately, their result was never confirmed. Later surveys did not find good BD candidates, but several very low mass stellar companions. In a survey of white dwarfs, [Becklin & Zuckerman 1988] turned up a very red and faint companion, GD 165B, whose spectrum was quite enigmatic. This was, in retrospect, the discovery of the first L dwarf. [Kirkpatrick et al. 1999] argue that it is also probably a BD, but that is hard to confirm (cf. the chapter by Cushing in this volume).

The next good candidate BD came from a radial velocity survey. [Latham et al. 1989] were conducting a survey of about 1000 stars with 0.5 km/s precision. Among their roughly 20 radial velocity standards, HD 114762 exhibited periodic variability just at their limit of detectability. Its orbit has been confirmed by the precision radial velocity groups, and implies a lower mass limit for the companion of about 11 $M_{\rm jup}$. The difficulty is that its orbital inclination is not known, and it is one of very few objects in the "brown dwarf desert" [Grether & Lineweaver 2006]. This term refers to the dearth of BDs as close companions to solar-type stars, confirmed by the results of many radial-velocity extrasolar planetary searches. With so few real objects in a large sample, it is possible that any given one is a stellar mass companion seen nearly pole-on.

Oppenheimer describes in another chapter the discovery of the companion to a low-mass star that has come to be accepted as the "first incontrovertible brown dwarf" . Gl 229B was first detected in 1994, but the group showed commendable forbearance in waiting for proper motion confirmation that it was physically associated with the primary (allowing the known parallax of the primary to be applied to find its luminosity). They also obtained a spectrum that confirmed the remarkably low temperature implied by its luminosity [Oppenheimer et al. 1995]. In particular, the spectrum contains methane bands at 2 microns; features that had previously been detected only in planetary atmospheres (and which are not expected in any main sequence star). This has now become the defining characteristic of T dwarfs. The announcement of Gl 229B came at the same Cool Stars conference in Florence in October 1995 as the discovery of the first extrasolar planet. Thus 1995 was the year when the substellar domain was fully opened to observations.

1.2 Brown Dwarfs in the Field

The most straightforward and unbiased sort of search is to simply look for BDs "in the field", meaning at random locations in the sky. Once all-sky surveys at appropriate wavelengths (DENIS and 2MASS) became possible in the mid-1990s, the discovery of field BDs became much easier (none were identified before that time). The DENIS survey began in 1996 but conducted a pilot survey in 1995. It has one optical color (I) and two infrared colors (J, K), and operated primarily in the southern hemisphere. The 2MASS survey began regular operations in 1997 but was obtaining excellent data in a prototype survey by 1995. It uses the three near-infrared colors (J,H,K), and operated primarily in the northern hemisphere. Both surveys had published discoveries of field L dwarfs by 1997 ([Kirkpatrick et al. 1997] and [Delfosse et al. 1997]).

Because BDs are particularly faint, it is very difficult to see them unless they are nearby. This makes proper motion surveys a promising search tactic (if they are deep and red enough). One important early discovery was the culmination of a long search for faint red objects with high proper motion (the Calan-ESO survey). A red spectrum of a candidate was obtained [Ruiz et al. 1997] that shows the features now associated with the L dwarfs. The team dubbed the object "Kelu-1" (a Chilean native word for "red"). It also showed lithium, making it a certified BD. This discovery was closely followed by one of the DENIS objects [Martìn et al. 1997].

One generally has the problem that any BDs which are in the temperature range also inhabited by main sequence stars will be hard to distinguish as substellar. This includes all objects in the late-M spectral class, and the early half of the L dwarfs (although we still are not certain which L spectral subclass corresponds to the first guaranteed BDs). The only way to distinguish stellar from substellar objects above the minimum main sequence temperature in the field is through the lithium test. Even for companion objects, it is very difficult to find systems in which substellar certification can quickly be accomplished dynamically. To conduct the lithium test, however, requires a medium dispersion spectrum with sufficient signal-to-noise. This test has still not been conducted on most possible BDs. For example, one of the currently known field BDs (LP 944-20, M9) was only shown to be a BD when such a spectrum was taken by [Tinney 1998], long after its discovery as a late M star in a proper motion survey. We discuss the lithium test in more detail later, but its primary utility is that any object which is M8 or later and shows lithium is guaranteed to be substellar [Basri 1998].

1.3 Brown Dwarfs in Young Clusters and Star-Forming Regions

It is actually easier to see young BDs, because they are not as faint and cool as the older ones. Finding young objects in the field, however, is hard since they will constitute only a small fraction of possible targets. This means that searches are best conducted in young clusters (none of which are particularly near to us, except the relatively recently discovered TW Hya group). Of course, the closer the cluster is, the larger the total angular area that it will cover (making surveys more costly in telescope time and making the identification of cluster members from field stars harder). There is therefore a trade-off to be made between the distance, age, and richness of different clusters. The closest star-forming regions (groups less than about 10 Myr old) are at distances of 150 pc or further. They have the advantage, however, that even relatively low-mass BDs are still in the late-M or early-L temperature range (as well as larger in radius), and therefore can be seen out to distances of several hundred parsecs.

During the early nineties, there were a number of surveys aimed at finding BDs in young clusters and star-forming regions. [Forrest et al. 1989] announced a number of candidates in Taurus-Aurigae, which were later shown to be background giants [Stauffer et al. 1991]. Surveys of other star-forming regions (eg.

[Williams et al. 1995]) also found objects which might well be substellar, but with no obvious way to confirm them. [Hambly et al. 1993] conducted a deep proper motion survey of the Pleiades, and found a number of objects (labeled with the authors' initials: HHJ) that models suggested should be substellar. [Stauffer et al. 1994] were also conducting a survey for BDs in this cluster, working from color-magnitude diagrams. Both surveys went substantially deeper than before, and uncovered interesting objects. This set the stage for the next, ultimately successful, effort to find cluster BDs. Nonetheless, it is well to remember that at the 1994 ESO Munich conference on "The Bottom of the Main Sequence - and Beyond" (Tinney, ed.), there was a palpable sense of frustration at the failure of many efforts to confirm a single BD.

In star-forming regions, the BDs are at their brightest, so the mass function can be sampled all the way to the bottom of the BD mass range and below. Complications include variable extinction in the star-forming region, possible age spreads of order millions of years (Myr) for the objects (which are a larger fractional problem than with older clusters). The main problem is the reliability of evolutionary models which are almost exclusively the means by which masses are assigned to the individual objects. These are known to become increasingly questionable as one moves to lower masses and younger ages. The primary star-forming regions that were first studied are Taurus-Auriga, Orion (various sub-regions), σ Ori, IC 348, ρ Oph, Upper Sco, and Chamaeleon (various sub-regions); see [Basri 2000] for a summary. They have the advantage that one is truly measuring the *initial* mass function, as there has been no time for dynamical ejection of a substantial number of BDs.

2 My Search for the First Brown Dwarf

My own research had been concentrated on star formation for the decade before 1993. I came to the topic through an initial interest in stellar magnetic fields. T Tauri stars, which everyone felt in the 1970s must be very young stars, were still quite enigmatic at the beginning of the 1980s. One thing that was suggestive is that the emission line spectra from these objects looked a lot like the active Sun or even the flaring Sun. Thus one idea was that the source of emission was very strong magnetic activity on these stars. Another was that the emission arose from either accretion or outflow activity. It turns out that all these ideas are simultaneously correct; the T Tauri stars are very young (still forming) stars which exhibit strong magnetic activity, magnetospheric accretion from an accretion disk, and strong outflows. As they age, the accretion and outflow activity wanes, but they remain very magnetically active. The relevance is that I was driven through these investigations to become familiar with young stars and low mass stars.

In 1993 a new opportunity arose for California astronomers. The first Keck telescope, which had been designed at UC Berkeley and UC Santa Cruz with instrumentation from there and Caltech (and major funding from Caltech) was about to be opened to our community. I think most of us tried to think of a really impactful project, given the 10-m aperture that we soon would have access to. I naturally thought about new projects involving T Tauri stars, but I also sat down with some of my friends to discuss other possibilities. Geoff Marcy and I had been collaborating for some time on magnetic studies of stars, while he also struggled to eke enough precision out of the high resolution echelle spectrograph at Lick Observatory to detect exoplanets using the Doppler effect. Most of my own work also involved high resolution spectroscopy, and the HIRES spectrograph at Keck was going to be like the Hamilton echelle we were familiar with, only perhaps 50 times faster! Our colleague James Graham was also interested in high resolution spectroscopy (among other things) and low mass stars. It was James who suggested we might pursue the discovery of BDs via the lithium test.

Graham's suggestion that we pursue the lithium test made immediate sense to me. I had become familiar with lithium as an astrophysical diagnostic in initial work with Eduardo Martín and Claude Bertout in the context of lithium as a signpost of youth in T Tauri stars. In that instance the mass range of stars under consideration (0.5-1 solar mass) burn their lithium in a few 10s of Myr, but before that they display strong lithium lines (being relatively cool). This affords a nice way to distinguish post-T Tauri stars from older stars, and to put a limit on how old they are. Our work also showed, however, that one must be relatively careful to have the right effective temperature in interpreting an observed lithium line strength. What appears to be lithium depletion can simply be an error in interpreting a temperature to be a couple hundred degrees hotter than it really is.

Martín had moved on to do his thesis work with Rafael Rebolo at the Instituto d'Astrofisico de Canarias (IAC). It was Rebolo's group who first proposed the lithium test for substellar objects [Rebolo et al. 1992]. Their suggestion inspired us to make this our Keck project (though of course we each had other projects as well). Naturally the group at the IAC had also embarked on an effort to apply the lithium test to the best existing BD candidates. They used 4-m class telescopes at spectral resolutions ($\frac{\lambda}{\Delta\lambda}$) of 14000 for a brighter initial sample [Magazzù et al. 1993]. This sample included several of the coolest known field objects (late M dwarfs). They were easily able to detect lithium in the cool (M6) T Tauri star UX Tau C, but not in any of the test objects. That object is unfortunately too young for the lithium test to work, since stars won't have had time to deplete their lithium yet.

2.1 Distinguishing Stars from Brown Dwarfs: The Lithium Test

Stars and BDs can have identical temperatures and luminosities when they are young (though the star would have to be older than the BD). "Young" in this context extends up to a gigayear or so. We therefore require a more direct test of the substellar status of a young BD candidate before it can be certified. Since the difference between BDs and very low mass stars lies in the nuclear behavior of their cores, it is natural to look for a nuclear test of substellarity. There is a straightforward diagnostic that is fairly simple both theoretically and observationally: the lithium test. In addition to verifying substellar status, observations of lithium can be used to assess the age of stars in clusters, which is helpful in the application of the lithium test itself. Lithium observations of very cool objects can be useful in constraining the nature of BD candidates in clusters, in the field, and in star forming regions.

In the simplest terms, stars will burn lithium in at most 100 Myr, while most BDs will never reach the core temperature required to do so. This stems from the fact that even before normal hydrogen burning commences, core temperatures in a star reach values that cause lithium to be destroyed. On the other hand, in most BDs the requisite core temperature is never reached because of core degeneracy. Furthermore, at masses near and below the substellar boundary the objects are all fully convective, so that surface material is efficiently mixed through the core. Finally, the surface temperatures of young candidates are favorable for observation of the neutral lithium resonance line, which is strong and occurs in the red. There are some subtleties to be considered in the application of the test, as discussed below. A more comprehensive review of this subject is provided by [Basri 1998].

The idea behind the lithium test was implicit in calculations of the central temperature of low mass objects by [D'Antona & Mazzitelli 1985] and others. They found that the minimum lithium burning temperature was never reached in the cores of objects below about 60 $M_{\rm jup}$. On the other hand, all M stars on the main sequence are observed to have destroyed their lithium. The first formal proposal to use lithium to distinguish between substellar and stellar objects was made by [Rebolo et al. 1992]. This induced [Nelson et al. 1993] to provide more explicit calculations useful in the application of the lithium test.

The theory of lithium depletion in very low-mass objects is comparatively simple. Because the objects are fully convective, their central temperature is simply related to their luminosity evolution. The physical complications in very low-mass objects, including partially degenerate equations of state and very complicated surface opacities, do not obscure the basic relation between the effective temperature and lithium depletion. The complications of mixing theory, which lead to many fascinating effects in the observations of surface lithium in higher mass stars, are simply not relevant for fully convective objects.

2.2 Querying the Seven Sisters

One would like to study stars of a known age that are sufficiently old that essentially all stars will have depleted their lithium, but not much older (so that the very low-mass objects are as bright as possible, since they fade with time). Of course one also wants a cluster that has been well surveyed forvery low-mass objects and that is relatively close (so they are brighter). The Pleiades cluster (also known as the ”Seven Sisters”) seemed the ideal hunting ground as there were a number of studies recently published and searches continuing. We selected the study of [Hambly et al. 1993] as our source of targets, and simply resolved to continue searching for lithium at the faintest end of known Pleiades objects. At that time everyone understood the age of the Pleiades to be 70 Myr. One could take theoretical models (for example, those of [Nelson et al. 1993]) and translate them to color-magnitude diagrams for different masses and ages. These implied that the faintest known Pleiades objects should already be BDs (with masses around 60 $M_{\rm jup}$).

With HIRES at Keck, we could achieve spectral resolutions of 30000 even for the faint Pleiades objects, although it required exposures of a few hours. This allowed us to place upper limits on the equivalent width of the lithium line in the objects HHJ 3 and HHJ 14 of under 200 mÅ[Basri et al. 1994]. The strength of the resonance line means that it does not begin to desaturate until more than 90% of the initial lithium has been depleted. The timescale over which the lithium line disappears in stars is about 10 Myr, which is roughly 10% of the age at which it occurs in substellar objects. But the observational disappearance of the line occurs even more rapidly (after desaturation). We could make a strong argument that lithium was essentially depleted in these objects, which is incompatible with their theoretical substellar mass. We also had good empirical reasons to believe that the lithium line should be strong in a BD at the temperature of our targets since it was seen in UX Tau C [Magazzù et al. 1993]. Given the (not yet known) spectral type of the lithium boundary in the Pleiades, this object is quite likely to be a BD itself in retrospect.

Our puzzling failure to find lithium had three possible explanations. One which we mentioned first but discarded because the consensus was tilting the other way, is that the Pleiades could be substantially older than thought at the time. We briefly discussed an age as high as 200 Myr. Another possibility, of course, is that the interior models are seriously wrong, leading to a wrong translation of a position in the color-magnitude or color-luminosity diagram into actual mass. The third is that the translation of color-magnitude into effective temperature (which is the actual variable in the interior models) is problematic. Because at that time this was known to be problematic and inconsistent for M dwarfs, and because of my previous experience with this sort of problem in T Tauri stars, we elected to chalk up the mystery to problems with the effective temperature scale.

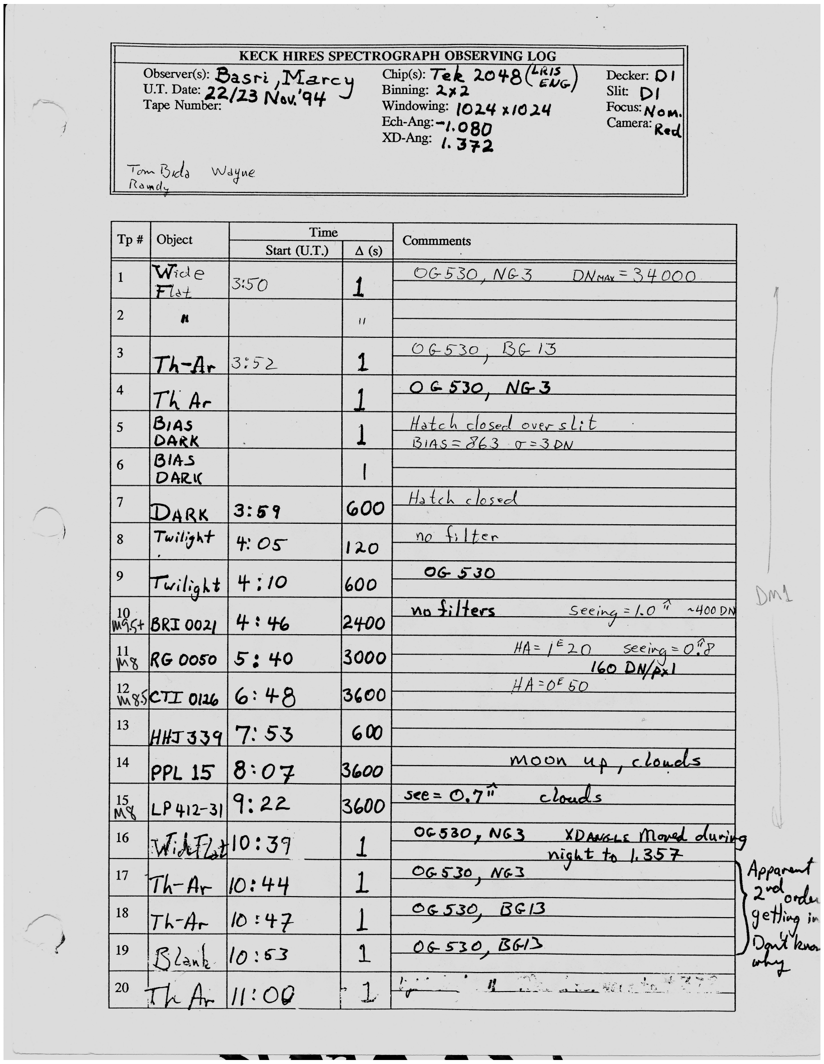
[Martìn et al. 1995] pursued a similar strategy as us but only had access to spectral resolution of a few thousand with 4-m telescopes (cf. the Chapter by Rebolo in this volume). Such observations are very difficult due to the faintness of very low-mass objects. They did not detect lithium in any of their candidates. For field targets (since the ages aren't known) this implied a lower mass limit greater than 60 $M_{\rm jup}$, but did not fully resolve whether they are BDs, because of the high upper limits to detectable lithium strength. Their results were also puzzling for their Pleiades candidates (though less constraining than ours). These were drawn from the same [Hambly et al. 1993] list of very faint proper motion objects, and those authors had already suggested BD candidacy based on the color-magnitude position of the objects compared to evolutionary tracks for the age of the Pleiades (thought to be 70 Myr). [Martìn et al. 1995] realized too that there was an inconsistency between the inferred mass of these Pleiades members and their lack of lithium.

2.3 Passing the Lithium Test

Meanwhile my group was waiting for even fainter Pleiades candidates to be found. Our break came when John Stauffer was preparing to publish the results of a survey he had been conducting for a few years for the faintest Pleiads at Palomar Observatory [Stauffer et al. 1994]. Candidates were dubbed with “Palomar Pleiades” numbers, and the object PPl 15 was first found on an exposure in 1989. John and I were friends and when I asked him if he had turned anything up, he generously provided a finding chart in advance of publication. His survey was photometric rather than a proper motion survey like HHJ had been conducting. PPl 15 was only a little fainter than HHJ 3, so in order for us to successfully detect lithium, the lithium depletion boundary would have to be fairly sharp in luminosity.

In November of 1994 we obtained the first high resolution spectra of PPl 15 (Fig. 1 shows the first page of the observing log). As noted in our subsequent paper [Basri et al. 1996] “at no time were observing conditions ideal”. There were cirrus clouds of varying thickness, and the gibbous Moon was about 60 degrees away, producing extra sky brightness (the star had only 5-10% the brightness of the sky). It was clear that this object (with an I magnitude barely brighter than 18) was near the limit of what could be done with HIRES at the resolution and signal-to-noise (S/N) that is needed. Geoff Marcy and I observed it six times over 2 nights with individual exposures of 60-90 minutes. Two of these were so plagued by clouds that we didn’t end up using them in our final sum. Traces of all our original spectra are shown in Fig. 2. The order containing lithium was barely visible in the raw images, so we did not know during the run whether lithium had been detected. We did do some preliminary spectral extractions on the mountain and it seemed possible that something was there, but not enough to make a note in the log. We quickly confirmed that PPl 15 had the right radial velocity and Hα strength to be a cluster member, in addition to fitting on the cluster color-magnitude diagram.

Once home I set about trying to get the maximum information out of the spectra. After reducing them the “normal” way I tried a couple of other techniques. The optical curvature of the orders could either be removed by a geometrical interpolation, or the spectrum could be extracted along curves that were pre-determined by brighter exposures. The sky could be treated several different ways (obviously sky subtraction is very important in such faint spectra). With some special consideration, we could also weight individual pixel rows according to their S/N. It became increasingly clear to me that there was a good chance we had detected lithium, but it was not unassailable. I had many other M6 dwarf spectra to compare PPl 15 with (including HHJ 3), and several of the PPl 15 spectra were unique in showing an absorption feature at just the right stellar wavelength. Its strength was not as great as expected from undepleted lithium, and there were some spectra in which one could not say that it was present with any confidence. I can remember the night I became finally convinced it was real; I savored the idea that for that brief time I was the only one who had a certified BD in my grasp. It turns out that isn’t quite true, because the groups working on Teide 1 and Gl 229B were also analyzing their data, but we didn’t know about each other’s discoveries.



KECK HIRES SPECTROGRAPH OBSERVING LOG

Observer(s): Basri, Marcy
U.T. Date: 22/23 Nov.'94
Tape Number:

Chip(s): Tek 2048 (LRIS ENG)
Binning: 2x2
Windowing: 1024 x 1024
Ech-Ang: -1.080
XD-Ang: 1.372

Decker: D1
Slit: D1
Focus: Nom.
Camera: Red

Tom Bida Wayne
Randy

Tp #	Object	Time		Commments
		Start (U.T.)	Δ (s)	
1	Wide Flat	3:50	1	OG530, NG3 DN_{MAX} = 34000
2	"		"	
3	Th-Ar	3:52	1	OG530, BG13
4	Th Ar		1	OG530, NG3
5	BIAS DARK		1	Hatch closed over slit BIAS = 863 σ = 3 DN
6	BIAS DARK		1	
7	DARK	3:59	600	Hatch closed
8	Twilight	4:05	120	no filter
9	Twilight	4:10	600	OG 530
10 M9.5+	BRI 0021	4:46	2400	no filters seeing = 1.0" ~400 DN
11 M8	RG 0050	5:40	3000	HA = $1^{E}20$ seeing = 0."8 160 DN/pxl
12 M8.5	CTI 0126	6:48	3600	HA = $0^{E}50$
13	HHJ 339	7:53	600	
14	PPL 15	8:07	3600	moon up, clouds
15 M8	LP 412-31	9:22	3600	see = 0.7" clouds
16	Wide Flat	10:39	1	OG530, NG3 XDANGLE Moved during night to 1.357
17	Th-Ar	10:44	1	OG530, NG3
18	Th-Ar	10:47	1	OG530, BG13
19	Blank	10:53	1	OG530, BG13
20	Th Ar	11:00	1	[illegible]

DM1

Apparent 2nd order getting in Don't know why

Fig. 1 The observing log from the first night of the run where we began observing PPl 15. The handwriting is mostly Geoff Marcy's; I was on the computer doing initial IDL reductions. We were still experimenting with order sorting filters (there is a puzzle noted at the bottom) but it didn't affect the PPl 15 observations. Both clouds and the Moon were noted. We observed HHJ 339 first because it was brighter (see 3.3 for its story). The other objects were on our "bottom of the main sequence" program.

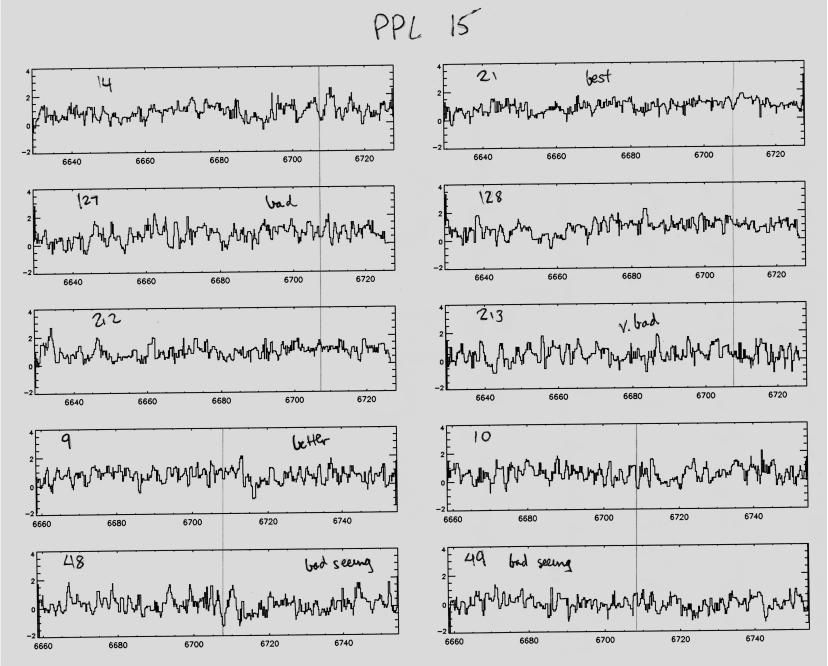


Fig. 2 A plot I made for the group of the raw spectra obtained of PPl15 in Nov. 1994 (top 6) and Mar. 1995 (bottom 4). The numbers above each spectrum refer to the index number in our observing logs, with a few comments. The location of the lithium line is marked with a vertical line in each spectrum.

I felt that it would really be much better if we could nail the detection down more solidly, so we returned in March 1995 to re-observed PPl 15. Unfortunately the lack of cirrus was more than compensated for by a combination of bad seeing and the fact that the Moon was now much closer to the object. The sky contribution ended up being about twice as much relative to the star as in November. The spectra really did nothing to confirm the lithium detection (actually they decreased my confidence). It turns out there was also an astrophysical reason why lithium was less visible in PPl 15 in March, but we didn't find that out until a couple of years later (see Section 2.6). At this point it became something of a "gut call". I consulted with my co-authors, and we finally decided that our final best reduction of all the spectra contained a clear enough signal that we could publish (Fig. 3).

2.4 The Invention of Lithium Dating

Of course, now we had to explain how lithium could appear in PPl 15 but not in HHJ 3. We first made an empirical bolometric correction to the color-magnitude data

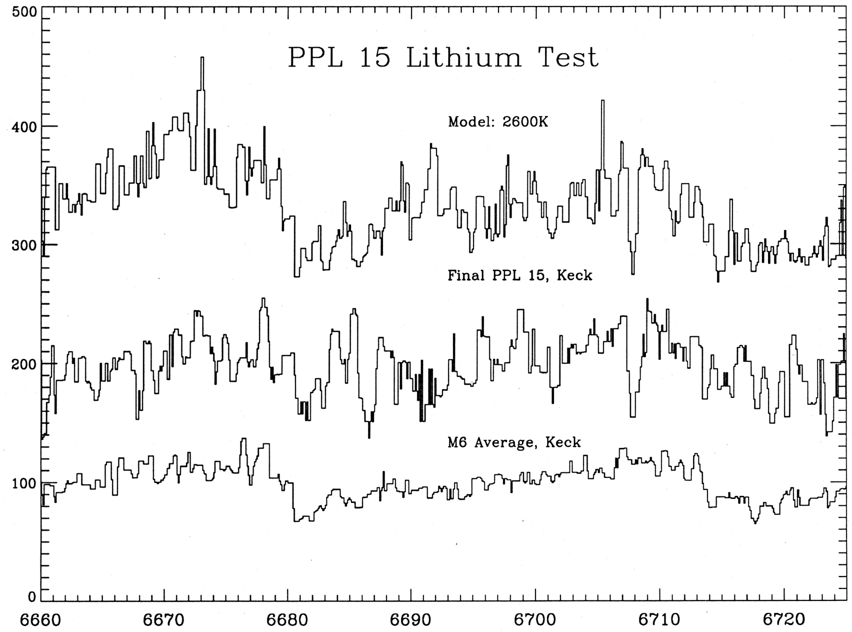


Fig. 3 A final version of the lithium detection that we used to help us decide to publish the result. After a lot of processing of the individual spectra in Fig. 2 and weighting of spectra by their quality, it seemed clear that we really detected the line with publishable confidence. The spectrum resembled what we expected on the basis of model atmospheres, and the feature at 6706Åclearly did not show up in M dwarf spectra even with higher S/N. The molecular bands in this part of the spectrum have similar amplitudes.

to convert to luminosity (models compute luminosity and effective temperature). James Graham also observed the faint Pleiads in the infrared, providing a nice check on the bolometric correction. After a set of careful complementary approaches, we adopted final logarithmic bolometric luminosities for HHJ 3 and PPl 15 of -2.78 and -2.88 respectively (in solar units). We also had to discuss the distance modulus to the cluster (which was a bit uncertain) to convert apparent to intrinsic brightness. We then used the models of [Nelson et al. 1993] to convert luminosity to mass, and also to understand the lithium depletion with age. These models were consistent with others of the time (eg. [D'Antona & Mazzitelli 1985]) and these authors kindly provided us with fine grids to use. We were reasonably conservative, and also considered the range of uncertainties, but it was clear once again that for the canonical age of the Pleiades (we used 75 Myr) both these objects should be BDs and both should show lithium. HHJ 3 clearly did not, and PPl 15 appeared to have partially depleted lithium. This was not a surprising possibility given that it was barely fainter than HHJ 3 and could be just on the cusp of the depletion boundary.

At that point I revisited the possible explanations for the discrepancy. Unlike the situation in the first paper, we now had found the lithium boundary and knew what the objects that straddled the boundary were like. The proposition that the models were seriously wrong didn't look like the best bet. These objects are fully convective and at that age basically powered by gravitational contraction. The only nuclear burning that should have taken place is deuterium burning. All these things are relatively simple and should be relatively well understood. The proposition that the effective temperature scale was the problem had now effectively been dealt with by using bolometric luminosity instead. That left the age hypothesis. My insight clarified as I looked at the "waterfall diagram" shown in Fig. 4 that I constructed from our model data. This shows the abundance of lithium as a function of age and mass for very low mass objects straddling the substellar boundary. It became clear to me that I could put HHJ 3 and PPl 15 (and later Teide 1) onto this diagram given their different lithium strengths with slightly different masses and the same age but only if the age of the Pleiades was substantially older than what everyone thought it was. This reasoning appears in [Basri et al. 1996] in Fig. 5, with the more empirical bolometric luminosity in place of mass and reduced to a two-dimensional presentation. The observed luminosity of HHJ 3 combined with its lack of lithium force its age to be greater than 110 Myr, while the same quantities for PPl 15 force its age to be less than 125 Myr.

It didn't take me long after starting to look into this idea to find that it wasn't as radical as it first seemed. The canonical age of the Pleiades was derived in the usual fashion: by looking at the massive stars that are just turning off the main sequence. For a cluster like the Pleiades these objects have convective nuclear burning cores and radiative envelopes. Stellar evolutionists had by then been discussing for a few years what the effects of convective overshoot in the core would be. Very simply, such overshoot would reach into the unburned hydrogen of the radiative envelope and make some small fraction of it available for burning. This would allow core hydrogen burning to last longer, thus increasing the age of the star when it turned off. We cited a number of papers that discussed convective overshoot (eg. [Meynet et al. 1993]) and had inferred that the Pleiades might be as old as 200 Myr, though 100 Myr seemed more reasonable. This made it clear that our proposition that the Pleiades might be 115-120 Myr old was actually in line with advanced thinking of the time. Furthermore, the technique I had now developed (which I called "lithium dating") was itself a nuclear diagnostic of stellar age. The physics of lithium burning in a cool fully convective object is actually simpler and on firmer footing than for hydrogen core and shell burning in the presence of convective overshoot. Indeed, we suggested that lithium ages could be used to calibrate the amount of convective overshoot in massive stars.

In lithium dating the details of convection are rendered unimportant by the fully convective nature of the objects (which are forced onto adiabatic temperature gradients). The problem is so simple, in fact, that not long after developing my method I was discussing it with Lars Bildsten (at that time in the Berkeley Physics department). He decided it could be solved semi-analytically, and assigned it as a problem in his stellar structure class. It was a bit much for most of the students,

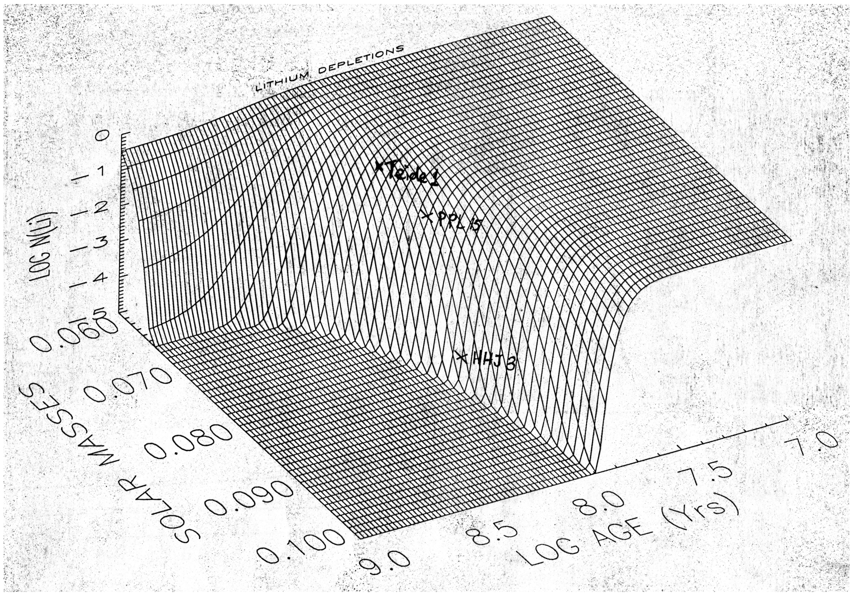


Fig. 4 A plot I made for myself when I was trying to understand how to reconcile the lack of lithium in HHJ 3 with the presence of lithium in PPl 15. The model data was from [Nelson et al. 1993] and the conversion from luminosity to mass for each object also relied in part on these models and in part on our method described in the text. The placement of the object with a lithium abundance also relied on model atmospheres. The placement in age I left as a free parameter, but expected that a proper solution would have all 3 cluster objects with similar ages. It became clear that such a solution existed, but at a substantially older age than was accepted for the cluster at that time.

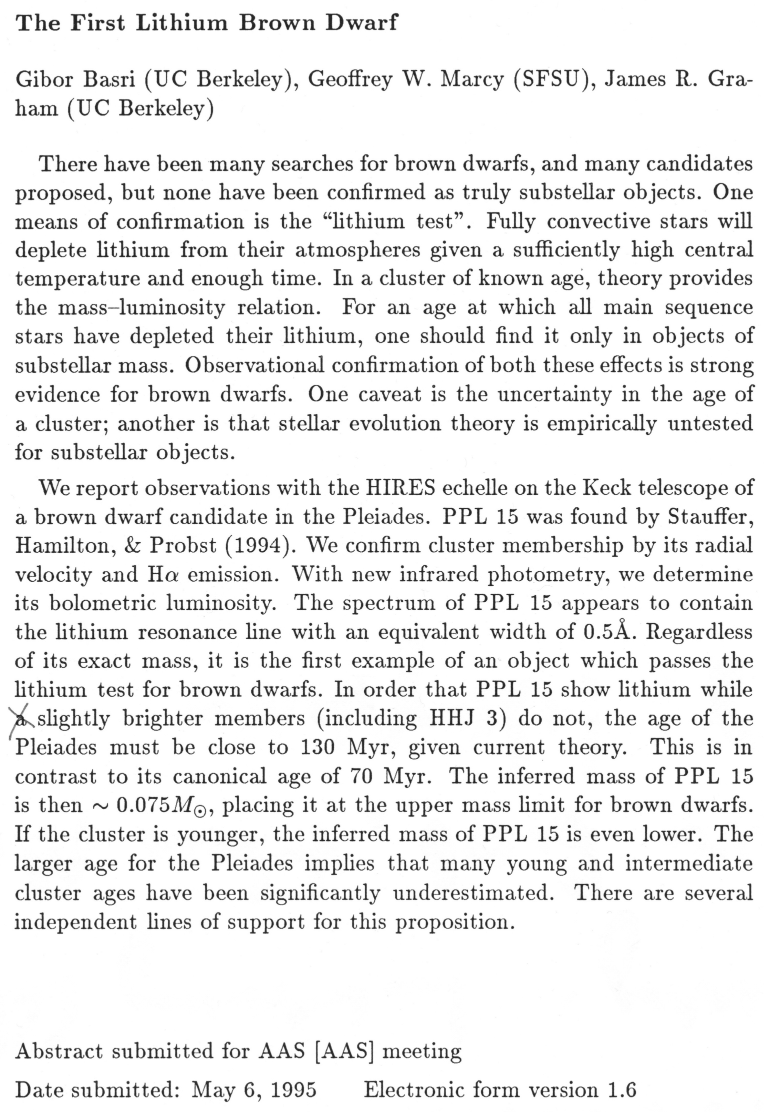
but one came close enough that they decided to turn the exercise into a paper. [Bildsten et al. 1997] make the point that the physics underlying lithium dating is really quite simple. As a cluster gets older, the luminosity of the lithium depletion boundary gets fainter. Thus, while the Hyades is one-third the distance of the Pleiades, its lithium boundary is at fainter apparent magnitudes because it is more than five times as old. Although α Per is further away, its youth means that the apparent magnitude of the lithium boundary is similar to the Pleiades. Given a correct age, the luminosity of the substellar boundary can then be inferred from models. This will not be coincident with the depletion boundary in general (only at the age of the Pleiades). Once the boundary is established, the search for BDs can proceed to fainter objects using cluster membership as the sole criterion. The precision of lithium dating is limited by the width of the depletion boundary, errors in the conversion of magnitudes to luminosities (due to bolometric corrections and cluster distances), and possible corrections to the age scale because of opacity issues in very cool objects. But it probably has similar precision to, and greater accuracy than, classical dating methods. Lithium dating can only work up to about 200 Myr, when the lowest mass object that can deplete lithium will have done so. Furthermore, the correction for core convective overshoot only applies for clusters younger than about 2 Gyr; stars leaving the main sequence in older clusters have radiative cores. There has been continuing controversy about the discrepancy between lithium and turnoff ages. There may be effects of stellar magnetic fields or other less simple physical effects that complicate things somewhat. [Burke et al. 2004] discuss these issues in more detail.

2.5 Presenting the First Brown Dwarf

By May 1995 we were convinced we had a real lithium detection, a real BD, and a proper explanation for the enigmatic results in the Pleiades to date. We considered publishing the results in *Nature* but decided against it. The main reason for our decision was that there was a rather sophisticated and new chain of reasoning that had to be gone through to understand our claims. Unlike what happened later that year with Gl 229B, PPl 15 didn't really appear to be any different from other M6 dwarfs except by virtue of its lithium line and age. Furthermore we were also revising the age scale for young clusters. On the other hand we recognized the importance of the result and wanted to get it out to other astronomers and the public. It was almost too late, but we submitted a late abstract to the June 6 AAS meeting in Pittsburg (Fig. 5), and were quickly invited to do a press release as well.

Explaining the lithium test to the public was clearly a bit of a challenge, and I worked with the UC Berkeley press officer (Bob Sanders) to make the attempt. The result was the explanation shown in Fig. 6. We wanted to deal with the complication that the Sun shows depleted but visible lithium, yet is clearly not a BD. This is as hard to explain as the age error due to convective overshoot (which we did not attempt to explain to the public). It is related in a way, in that the issue is again whether convection mixes material into the burning zone. For the Sun a classical model would say that the outer convection zone does not reach sufficiently deeply to mix surface lithium down to where it could be burned. Partially understood "anomalous mixing" mechanisms have to be invoked to explain the disparate lithium observations in the solar mass regime (even convective overshoot is not enough). We simplified this a great deal, and apparently reporters thought it comprehensible enough that our diagram appeared in many newspapers. The headline in the New York Times read "Big Telescope Is First to Find Brown Dwarf, Team Reports". The San Francisco Chronicle reported "Astronomers Find Cosmic Missing Link", and a modified color version of Fig. 6 appeared on the front page.

We submitted our paper to the Astrophysical Journal on July 7 1995, and it was accepted August 24. We presented the results to the first Keck Science meeting on Sept. 14 at Caltech (I recall that there were members of the Gl 229B team in the audience, who kept quiet). All of this was before the other "first" announcements of the discovery of BDs. Despite that, we are often not thought of as the clear and sole discoverers of BDs for several reasons (I wonder if it would be different had we decided to submit to *Nature* in June). One of them is that [Basri et al. 1996] did



The First Lithium Brown Dwarf

Gibor Basri (UC Berkeley), Geoffrey W. Marcy (SFSU), James R. Graham (UC Berkeley)

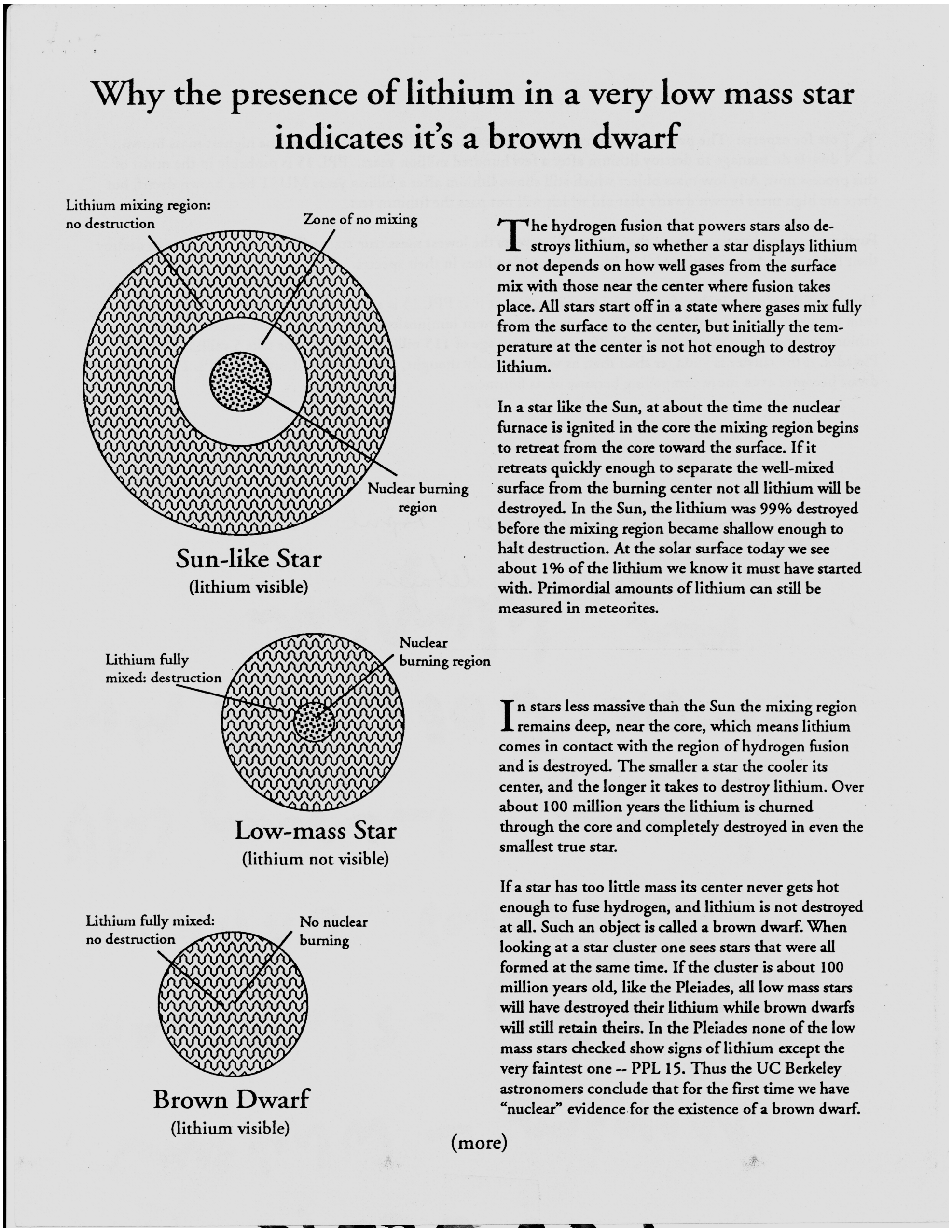
There have been many searches for brown dwarfs, and many candidates proposed, but none have been confirmed as truly substellar objects. One means of confirmation is the "lithium test". Fully convective stars will deplete lithium from their atmospheres given a sufficiently high central temperature and enough time. In a cluster of known age, theory provides the mass–luminosity relation. For an age at which all main sequence stars have depleted their lithium, one should find it only in objects of substellar mass. Observational confirmation of both these effects is strong evidence for brown dwarfs. One caveat is the uncertainty in the age of a cluster; another is that stellar evolution theory is empirically untested for substellar objects.

We report observations with the HIRES echelle on the Keck telescope of a brown dwarf candidate in the Pleiades. PPL 15 was found by Stauffer, Hamilton, & Probst (1994). We confirm cluster membership by its radial velocity and Hα emission. With new infrared photometry, we determine its bolometric luminosity. The spectrum of PPL 15 appears to contain the lithium resonance line with an equivalent width of 0.5Å. Regardless of its exact mass, it is the first example of an object which passes the lithium test for brown dwarfs. In order that PPL 15 show lithium while ~~a~~ slightly brighter members (including HHJ 3) do not, the age of the Pleiades must be close to 130 Myr, given current theory. This is in contrast to its canonical age of 70 Myr. The inferred mass of PPL 15 is then $\sim 0.075 M_{\odot}$, placing it at the upper mass limit for brown dwarfs. If the cluster is younger, the inferred mass of PPL 15 is even lower. The larger age for the Pleiades implies that many young and intermediate cluster ages have been significantly underestimated. There are several independent lines of support for this proposition.

Abstract submitted for AAS [AAS] meeting

Date submitted: May 6, 1995 Electronic form version 1.6

Fig. 5 My copy of the abstract submitted to the June 1995 meeting of the American Astronomical Society, which formed the basis of our public announcement of the first brown dwarf. I later noticed a small grammatical error.



Why the presence of lithium in a very low mass star indicates it's a brown dwarf

Sun-like Star
(lithium visible)

Low-mass Star
(lithium not visible)

Brown Dwarf
(lithium visible)

The hydrogen fusion that powers stars also destroys lithium, so whether a star displays lithium or not depends on how well gases from the surface mix with those near the center where fusion takes place. All stars start off in a state where gases mix fully from the surface to the center, but initially the temperature at the center is not hot enough to destroy lithium.

In a star like the Sun, at about the time the nuclear furnace is ignited in the core the mixing region begins to retreat from the core toward the surface. If it retreats quickly enough to separate the well-mixed surface from the burning center not all lithium will be destroyed. In the Sun, the lithium was 99% destroyed before the mixing region became shallow enough to halt destruction. At the solar surface today we see about 1% of the lithium we know it must have started with. Primordial amounts of lithium can still be measured in meteorites.

In stars less massive than the Sun the mixing region remains deep, near the core, which means lithium comes in contact with the region of hydrogen fusion and is destroyed. The smaller a star the cooler its center, and the longer it takes to destroy lithium. Over about 100 million years the lithium is churned through the core and completely destroyed in even the smallest true star.

If a star has too little mass its center never gets hot enough to fuse hydrogen, and lithium is not destroyed at all. Such an object is called a brown dwarf. When looking at a star cluster one sees stars that were all formed at the same time. If the cluster is about 100 million years old, like the Pleiades, all low mass stars will have destroyed their lithium while brown dwarfs will still retain theirs. In the Pleiades none of the low mass stars checked show signs of lithium except the very faintest one -- PPL 15. Thus the UC Berkeley astronomers conclude that for the first time we have "nuclear" evidence for the existence of a brown dwarf.

(more)

Fig. 6 The figure in the UC Berkeley press release that discussed how the lithium test can give certification of substellar status. We included the situation for the Sun (complicated), low mass stars (simple) and BDs (also simple, but we left out the wrinkle of behavior between 60-75 M_{jup}).

not actually appear in print until Feb. 1996 (by which time the two *Nature* papers on Teide 1 and Gl 229B had already been several months in print). At that time preprint servers were not yet in general use. Another is that both the possibly partial depletion of lithium and the most conservative (high) estimate of the mass of PPl 15 put it near the substellar boundary. It was therefore less definitive to many astronomers for whom the lithium test was new. Finally there was the issue of lithium dating itself; it was both a new technique and it challenged the very entrenched method of dating clusters by their upper main sequence turnoffs. Of course if one did not accept the revised age then the object moved more safely into the substellar regime. None of these issues ultimately proved to be a problem – PPl 15 is now quite definitely known to be substellar – but they delayed general acceptance of the result long enough to dilute it.

The effect of revising age significantly older is to increase the inferred masses of all the Pleiades very low-mass objects, so that HHJ 3 falls comfortably in the stellar domain, and PPl 15 moves up near (but not above) the substellar boundary. One could then quibble (and some did) about whether PPl 15 was a "true" BD or should be thought of as a transitional object. We admitted that it was transitional in some sense; in fact high mass BDs (between 60 and 75 M_{jup}) will eventually deplete lithium and engage in temporary hydrogen burning, but never stabilize themselves this way and so never become main sequence stars. Only by adopting the largest plausible age correction could one push PPl 15 up near the substellar boundary; the less the age correction the less its inferred mass.

In any case, the obvious prediction was that any cluster members that are fainter than PPl 15 should show strong lithium and be further into the substellar domain. This was the situation that allowed [Rebolo et al. 1995] a few months later to publish the fainter Pleiades member Teide 1 in *Nature* and assert (correctly) it is an obvious BD, without having actually done the lithium test. Such a claim could only be credible after we had announced our results on PPl 15. Although Teide 1 is a couple of spectral subclasses cooler than PPl 15, without the lithium detection in PPl 15 there was no guarantee that Teide 1 is below the lithium depletion boundary and therefore a true BD. There were a number of previous Pleiades objects that were expected to be BDs on the basis of their luminosity and temperature, but later failed the lithium test. A viewgraph I used sometime in 1996 to summarize the lithium results for the first Pleiades BDs is shown in Fig. 7. In early 1996 Marcy and I teamed up with Rebolo, Zapatero Osorio, and Martín to perform the lithium test at Keck on Teide 1 (and another nice object the IAC group found: Calar 3). This was done at lower resolution but good S/N given the objects' faintness [Rebolo et al. 1996].

2.6 *Two for One: The Final Word on PPl 15*

A close look at Fig. 7 shows that the very low-mass Pleiads are somewhat spread away from the zero-age main sequence. Some authors had interpreted this as an age spread (and that was being debunked at around this time), but another good

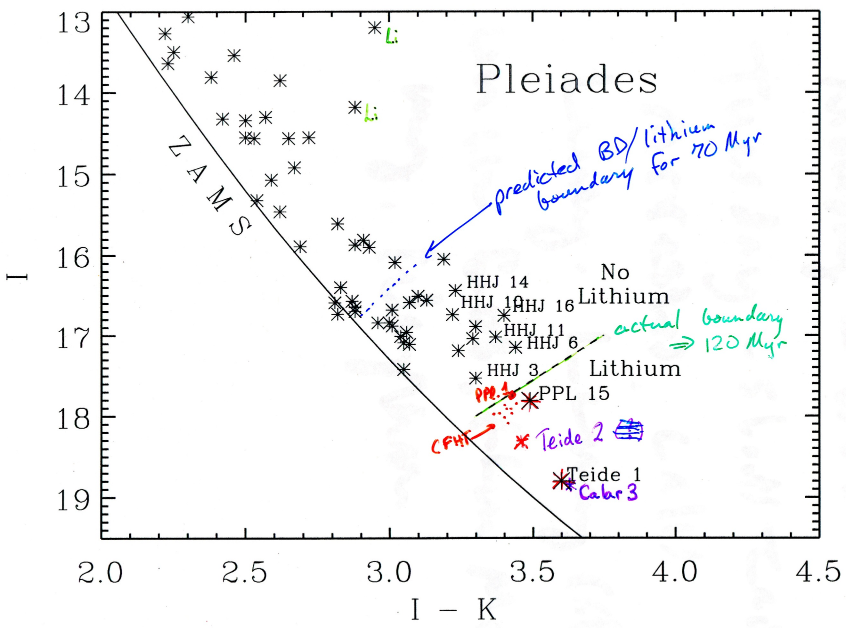


Fig. 7 A summary of the lithium constraints and lithium boundary for the Pleiades by mid-1996. All the labeled objects had been tested for lithium. Those above the "actual boundary" did not show lithium, while all objects tested below it did. The location of the expected boundary given the previously accepted age for the Pleiades of 70 Myr is also shown (which explains why the early results of the lithium test were so perplexing). Note the two objects near the top of the diagram that are also labeled "Li"; these are explained in Section 3.3.

explanation for it is the presence of binaries (after acknowledging that some of it is just observational uncertainty). More careful photometry lead the IAC group to wonder whether PPl 15 sits high enough off the zero-age main sequence that it might be binary. I realized that we had looked at the radial velocity of PPl 15 in one of our best spectra to confirm cluster membership, but had not repeated the determination for all the spectra. Of course, it seemed like it would be an incredible stroke of luck if the binary were close enough to show radial velocity variability (and even more so if it turned out to be a double-lined binary). Nonetheless, as soon as I performed the cross-correlation of PPl 15 spectra against UX Tau C, the correlation function was sometimes double-peaked! I immediately suspected that telluric lines were somehow fooling me, and spent about a week convincing myself that the effect was really stellar. There was no doubt that it was, as seen in Fig. 8.

It became rapidly apparent that the binary components were close to equal mass, and the period was very short. I could see substantial changes in the line positions from night to night. In order to get an orbit I would obviously have to return to HIRES and somehow arrange to get a whole series of nights in a row (at least for this object). I asked that my nights be scheduled within a week, and by good fortune

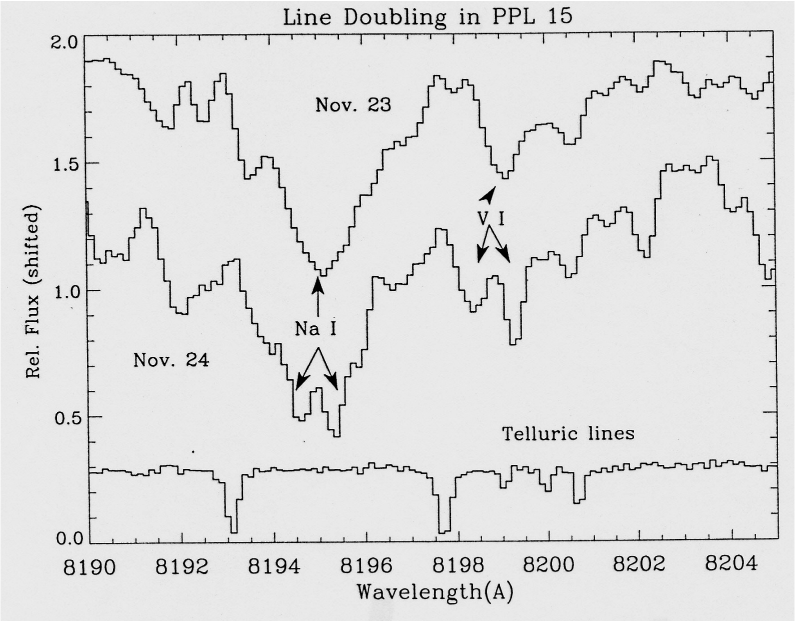


Fig. 8 An unpublished plot showing the line doubling in the spectrum of PPl 15, as seen from our first nights of observations (which we did not notice at the time). This proves that PPl 15 is a spectroscopic binary. The fact that the sodium and vanadium lines go from single to double one night later indicates that the orbital period must be quite short. The lithium detection was more obvious on the nights where the lines were not doubled. The bottom trace shows a hot star spectrum in which only telluric lines are visible (showing they are not responsible for the double lines above).

the other observers during that time turned out to be John Stauffer and Geoff Marcy. It had taken me a couple of years to convince John of the efficacy of lithium dating, but as an ace cluster observer once he was convinced he more or less took over the field, eg. [Stauffer et al. 1998], [Barrado et al. 1999], [Stauffer et al. 1999]. We were pleased with our former collaboration on PPl 15, so it took no effort to swap time during his nights with time during mine so I could get more orbital phase coverage. Geoff was happy to donate a little time from planet hunting to cooperate. The weather also cooperated just enough, and I got useable observations every night from Dec. 1-7 1997. Because I was no longer searching for lithium they could be substantially shorter; doing cross-correlations near the red end of the CCD range works just fine and the object is so red that it is much brighter there. We could easily include all the previous observations of PPl 15 as well. The final phase coverage and velocity variations are shown in Fig. 9.

The orbital period we found is roughly 6 days. This is a rather rare sort of close binary; it is a remarkable bit of serendipity that the first BD should have such a striking character. Fifteen years later, the number of BD binaries that are double-line spectroscopic binaries is still under five [Luhman 2012]. The separation of PPl

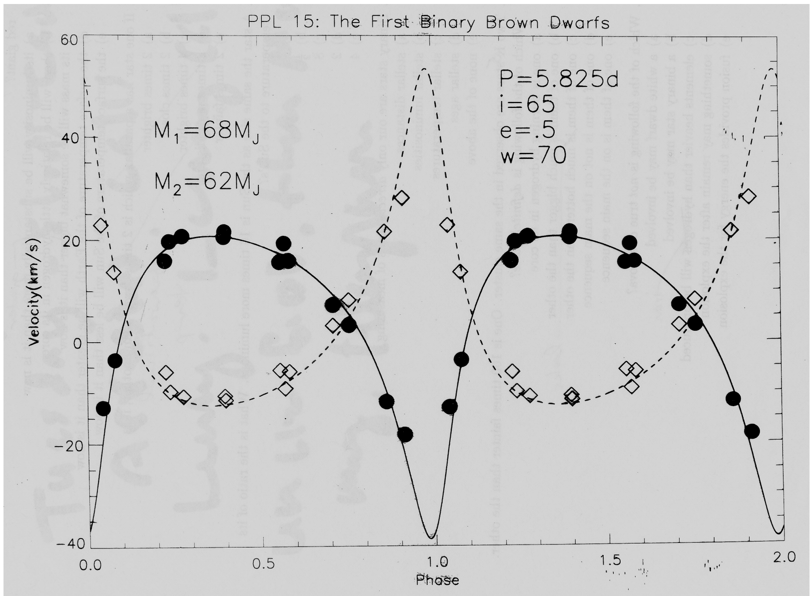


Fig. 9 An unpublished plot of the velocity observations for both components from the PPl 15 high resolution spectra taken with HIRES on Keck. Note that the orbit is fairly eccentric as well as very tight (short period).

15 is only 0.03 AU. There is a bias in magnitude-limited surveys in favor of finding binaries, but no particular advantage for such close ones. The binary is also quite eccentric (e=0.45); that is less uncommon and does not come close to violating tidal circularization timescales. We infer an inclination of about 50 degrees (this is not observed, but is compatible with the dynamical constraints on the system). We speculated that low mass systems might also have generally lower separations, or that the system is a result of an altered triple. Even now there are few double-lined substellar systems known.

This was during the time that Eduardo came to Berkeley to work with me, so we attacked the question of the binary properties. We could see both components, and the width of the correlation function also gave us their rotational broadening. Both binary components are unusually slow rotators for very low-mass Pleiads, and have similar projected rotational velocities (about 10 km/s). The lines are of nearly equal strength, but their relative strength varies with wavelength indicating that one object is redder than the other. Although we don't know the orbital inclination, the fact that both objects are contributing similar amounts of red light allow us to use models to constrain the total system mass to about 0.13 solar masses. The mass ratio comes from the total velocity separation of the components (~0.87) and the behavior of the relative line intensities (0.8-0.9). The latter also suggest spectral types for the two components of M6 and M7 (compatible with the observed M6.5). Taking a mass ratio of 0.85 with the total mass implies component masses of 60 and 70 M_{jup}.

Thus both components are comfortably within the substellar domain, and the lower mass component probably will never deplete its lithium.

We could not measure the two separate components in the lithium order (S/N is too low) but we obtain an explanation of the results in our original work. The November 1994 spectra were partly taken at an orbital phase where the two components were close in velocity (which enhances the visibility of the lines), while the March 1995 observations were made at a large velocity separation (where the sky noise can attack each of the lines separately). Compounded with the extra lunar sky light, it is no surprise that the March observations did nothing to confirm the presence of lithium. The binary nature also introduces a couple of complications. First, the equivalent width for either of the components is less clear; the hot component presumably dominates the continuum but the cooler component should have a stronger line, and what is seen depends on the phase of the observation. The second is that the expected lithium depletion is different for the two objects (which have different masses). We concluded that it is not necessarily true that lithium is partially depleted in PPl 15 (it almost certainly isn't for the cooler component). The net effect of all this is that PPl 15 is not a transitional object but a pair of true BDs [Martìn et al. 1999a].

My collaborators and I were also involved in the first discoveries of resolved BD binaries. In 1998 we were involved in a survey to push ever fainter in finding Pleiades BDs in order to get some real information on the substellar mass function. One of the objects that lies significantly below the then well-established lithium boundary (CFHT-Pl-18) showed up as a resolved pair with a separation of a third of an arc sec (corresponding to about 40 AU at the distance of the Pleiades). [Martìn et al. 1999a] find that both components are clearly substellar if members of the cluster, with masses of 45 and 35 $M_{\rm jup}$. The separation and mass ratio would not be surprising if the system was stellar, giving an early indication that the formation processes could be similar. Our rate of success (1 out of 6 targets) was also consistent with stellar expectations. This was the first "visible" or resolved BD pair discovered, but it was still a cluster rather than a field object.

We also discovered the first field BD binary, in a two-target exploratory attempt using the NICMOS camera on the Hubble Space Telescope [Martìn et al. 1999b]. The targets were two of the first known field lithium BDs (discussed near the end of Section 3.1). It turns out that both of them are binary, although at the time the components of Kelu-1 had too low an angular separation to resolve. They were resolved a few years later as the binary orbit separated them on the sky [Liu & Leggett 2005]. The other target, DENIS 1228.2-1547, did reveal both components with an angular separation of 0.275 arc sec. They are nearly equal mass, and the lithium detection implies they are both less massive than 60 $M_{\rm jup}$, but the parallax was not well-known enough to convert a luminosity to a mass using evolutionary models (as we had done for CFHT-Pl-18). The fact that both targets turn out to be binary is partly a selection effect due to the fact that binaries are brighter, but it conveyed the impression that BD binaries must be fairly common. We now know that BD companions occur a little less often than M dwarfs, with a frequency of roughly 20% [Duchêne & Kraus 2013].

3 Further Adventures with Lithium

I refined and developed the method of lithium dating after the early successes and extended it to other clusters and field objects. This led to a summary review [Basri 1998] which advanced the adoption of the method by others. It should be clear that I had developed a very strong working relationship with a number of astronomers at the IAC headed by Rafael Rebolo, especially Eduardo Martín who subsequently came to Berkeley as a postdoctoral researcher for several years. This collaboration was very fruitful for all of us; the IAC had a lot of surveys in progress and access to lower dispersion spectroscopy, while I had access to high resolution spectroscopy at the Keck telescope and a long history of line profile analysis. I also had a good collaboration with the PHOENIX stellar atmospheres group [Allard et al. 1997]. Our collaboration was active past the turn of the millennium.

3.1 The Lithium Test in the Field

Can the lithium test be used for field objects, given that one will not generally know the age of an object? Clearly it works to distinguish main sequence M stars from BDs less massive than 60 jupiters (that was the original idea). [Basri 1998] refined the discussion of how to apply the lithium test in the field. Fig. 10 shows that the lithium depletion region, taken with the observed luminosity or temperature of the object, provides a lower bound to the mass and age (jointly) if lithium is not seen. Conversely, it provides an upper bound to the mass and age if lithium is seen. The temperature at which an object at the substellar limit has just depleted lithium sets a crucial boundary. It is the temperature below which, if lithium is observed, the object must automatically be substellar. More massive (stellar) objects will have destroyed lithium before they can cool to this temperature. A substellar mass limit of 75 jupiters implies a temperature limit of about 2700K for lithium detection, which roughly corresponds to a spectral type of M6. Thus, *any object M7 or later which shows lithium must be substellar.* This form of the test is easier to apply than that employing luminosity, which requires one to know the distance and extinction to an object. Otherwise they are equivalent.

One wrinkle is that it takes stars a finite amount of time to deplete their lithium. Thus, if an object is sufficiently young, it will show lithium despite having a mass above the hydrogen-burning limit (giving the possibility of a false positive in the test). On the other hand, the minimum mass for lithium destruction is below the minimum mass for stable hydrogen burning. Thus, if we wait long enough, the high mass BDs will deplete their lithium too (giving the possibility of a false negative in the test). For instance, the binary BDs Gl 569Ba and Bb have dynamical masses that prove they are substellar, yet lithium is not detected [Zapatero-Osorio et al. 2005]. In other cases, an object could lie in the temperature range where it might be a BD and show lithium, but the age would have to be known to be sure (it might be young enough that a very low-mass star has not had time to deplete lithium). A more

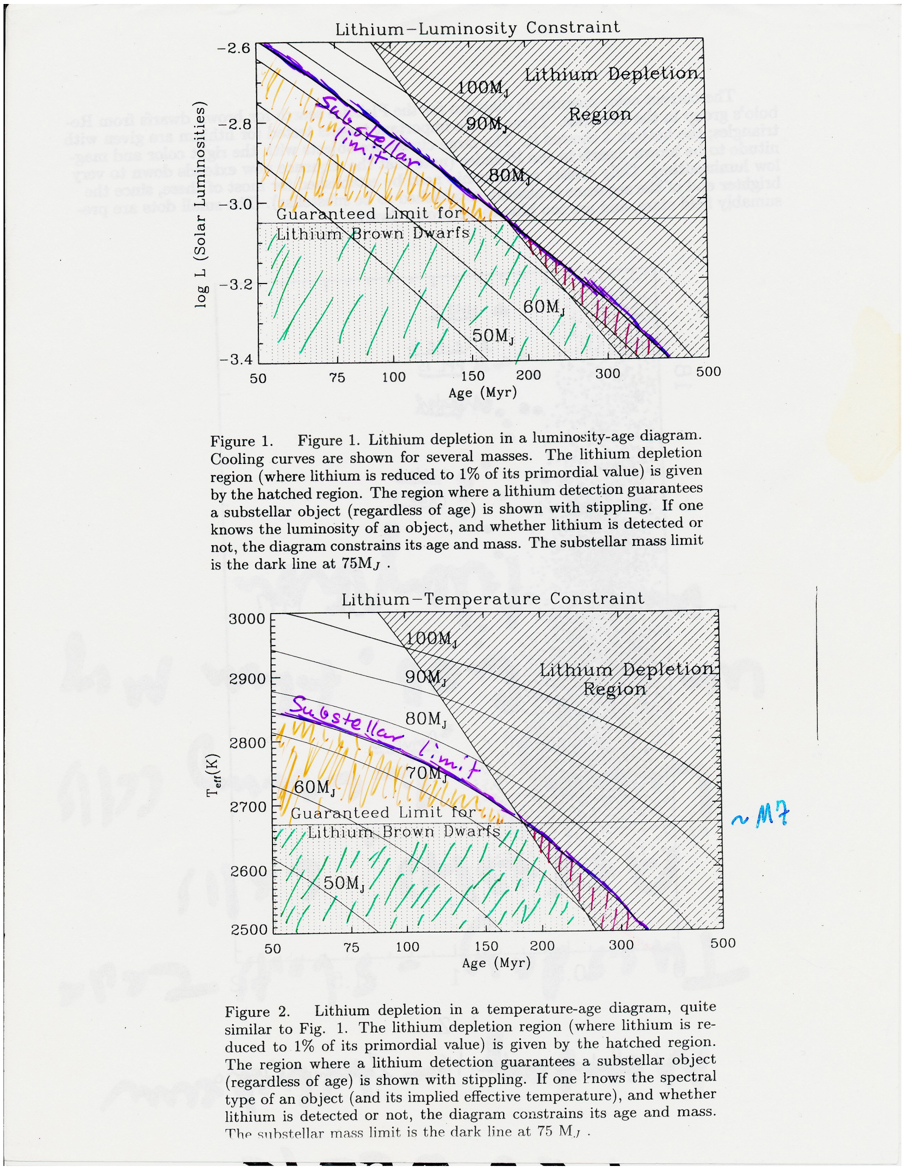


Figure 1. Figure 1. Lithium depletion in a luminosity-age diagram. Cooling curves are shown for several masses. The lithium depletion region (where lithium is reduced to 1% of its primordial value) is given by the hatched region. The region where a lithium detection guarantees a substellar object (regardless of age) is shown with stippling. If one knows the luminosity of an object, and whether lithium is detected or not, the diagram constrains its age and mass. The substellar mass limit is the dark line at $75M_J$.

Figure 2. Lithium depletion in a temperature-age diagram, quite similar to Fig. 1. The lithium depletion region (where lithium is reduced to 1% of its primordial value) is given by the hatched region. The region where a lithium detection guarantees a substellar object (regardless of age) is shown with stippling. If one knows the spectral type of an object (and its implied effective temperature), and whether lithium is detected or not, the diagram constrains its age and mass. The substellar mass limit is the dark line at 75 M_J .

Fig. 10 Summary viewgraphs I showed in talks on the use of lithium as a substellar diagnostic. The upper diagram is for luminosity and the lower diagram is for temperature of the object being tested. These quantities are shown as a function of age for various masses (the labeled curves). The stippled region (marked with green) is the region in which substellar status is guaranteed through this nuclear diagnostic. The diagrams show that the situation is more complicated above that region, since BDs may not have had time to deplete their lithium. For field objects, the age is generally unknown, so only the stippled region provides a guarantee of substellar status. Put simply, any dwarf object M7 or cooler which displays lithium must be a BD regardless of its age.

definitive case is provided by LP 944-20 [Tinney 1998]. It is sufficiently cool (M9) that the fact that lithium is detected guarantees it is a BD even though we know little about its age; the lithium detection provides an upper limit on the age. This is an example of an object that was known for quite some time before 1995 as a faint red object uncovered in a proper motion survey, whose substellar nature was completely hidden.

There were several large-scale field surveys underway at the time which had as one aim the discovery of field BDs. Two were major infrared surveys: 2MASS and DENIS. Another was a smaller proper motion survey. It was this latter that turned up the first field BD, dubbed Kelu-1 by [Ruiz et al. 1997]. That object was clearly cooler than any M dwarf (it resembled GD 165B, which was mentioned in Section 1.1) and it showed lithium, which guarantees that it is substellar. Shortly thereafter we applied the lithium test to a few of the most promising DENIS objects, and found lithium in DENIS 1228.2-1547 [Martìn et al. 1997]. This object was also cooler than the M spectral class, and it was clear that a new spectral class was needed to cover such objects (cf. the chapter by Cushing in this volume). It was in this paper that we formally proposed the L spectral class for the objects just under M dwarfs in temperature (which was adopted by the community). We showed that titanium oxide molecules had definitely disappeared, and were able to confirm the growing strength of the alkali lines, which dominate the optical spectra of cooler L dwarfs. On the other hand, our suggestion that Gl 229B also be included in the L spectral class was not adopted; the presence of methane in the spectra came to be a hallmark of the "T" spectral class.

3.2 The Lithium Test in Star Forming Regions

The lithium test is less obviously useful in star forming regions. Even clear-cut stars have not had time to deplete lithium yet. Nonetheless, there have been numerous reports of BDs in star-forming regions. They are identified as BDs on the basis of their position in color-magnitude or HR diagrams, using pre-main sequence evolutionary tracks (cf. the chapter in this volume by Baraffe). One must worry whether the pre-main sequence tracks for these objects are correct, or if there are residual effects of the accretion phase. If one of these candidates doesn't show lithium, it can be immediately eliminated a being a non-member of the star-forming regions. The lithium test as applied in the field still works: if a member of a star-forming region is cooler than about M7 (here we should be careful that the pre-main sequence temperature scale might be a little different) and the object shows lithium, then it must be substellar. Indeed, for an object to be so cool at such an early age pushes it very comfortably into the substellar domain.

Some very faint/cool objects have been found in star-forming regions whose substellar status seems relatively firm (if they are members). The lowest of these may be below the deuterium burning limit. Spectroscopic confirmation of these candidates is imperative, as has been done for a BD near the deuterium-burning boundary in σ Ori [Zapatero-Osorio et al. 1999]. A number of objects even fainter have been found in the past decade [Béjar et al. 2011]. Such observations indicate that the substellar mass function may extend right down through the lowest mass BDs into the planetary domain. It is natural to wonder how far it goes below that, since there is no obvious reason why it should stop just because deuterium burning ceases to function.

3.3 A Final Lithium Mystery in the Pleiades

Taking another look at Fig. 7 reveals one other very odd feature. There are 2 stars in the upper part of the diagram that appear to be pre-main sequence stars. These also arose from the search by [Hambly et al. 1993] and so have HHJ designations as well: 339 and 430. They therefore satisfy the cluster membership criteria of the other HHJ objects which played a pivotal role in defining the lithium depletion boundary in the Pleiades. Given the age of the cluster (especially after our upward revision) one certainly does not expect pre-main sequence stars (younger than 10 Myr) to still be present. The Pleiades is known for the pictures of it which show diffuse dust surrounding the bright stars (so one might be tempted to think it is still forming stars), but that nebulosity is well-known to be dynamically unrelated to the cluster. The cluster is simply passing through a diffuse interstellar cloud at the moment. Other authors had argued for a large age spread in the cluster, but those arguments did not stand the test of time.

Of course, if the stars really were pre-main sequence stars they would be comfortably above the substellar limit but should still show lithium given their youth. Shri Kulkarni had heard about the lithium test and my plans for the Pleiades from a colloquium I gave earlier in 1994 at Caltech, and decided his group should try it. He observed a number of HHJ stars near the lithium boundary (but not as faint as HHJ 3) in mid-October 1994, and included HHJ 430 in the list out of curiosity. I had the same curiosity, and observed HHJ 339 in the initial PPl 15 run in late November 1994. The non-detection of lithium in his faint HHJ targets is consistent with my group's non-detections, and provided further evidence that lithium depletion was complete above the depletion boundary.

Because of my success with PPl 15, and due to the fact that Ben Oppenheimer began to visit Berkeley in the years just after the announcement of Gl 229B, we eventually collaborated on a paper [Oppenheimer et al. 1997] which included these odd Pleiades objects. Both of them showed pronounced lithium, which was entirely consistent with their apparent pre-main sequence status (with the implication that they are indeed at about the distance of the Pleiades). Their ages do not appear to be any more than 20-30 Myr (and could be smaller). This conclusion is further supported by their levels of Hα emission. Their radial velocities provide further "proof" of cluster membership on the other hand, so the stars present a real conundrum. Taken at face value one might think that star formation had been going on for nearly 100 Myr in the cluster, yet there is no real evidence for intermediate age stars.

Ben and I eventually came up with an interesting dynamical explanation for them. [Oppenheimer et al. 1997] posit that the solution is one of dynamical history. Everything is moving in our Galaxy, and not just around the galactic center. We point out that given the positions and space motions of the cluster and the Taurus-Aurigae star forming region, it is not that unlikely that they intersected each other a few Myr ago. It would still be very difficult, however, for the Pleiades to actually capture stars from Taurus. Of more interest is the set of young stars which share very similar space motion with the Pleiades (although they are not co-located with it). This set of stars is sometimes referred to as the "Pleiades supercluster". Other stars with properties similar to HHJ 339,430 are kinematic members of this supercluster.

If one imagines a set of interstellar clouds with similar origin streaming along with similar space motions but somewhat different locations, there is no reason for them all to form stars at the same time. In particular, suppose there was a cloud that was closer to us but formed stars only 20-30 Myr ago, and was not dense enough to form a bound cluster. After they were born, the stars in this cloud would begin spreading apart, with velocities of a few km/s. Sufficient time passes that the leading edge of this burst of stars could actually be near the Sun. For example, the nearby very young and active star AB Dor is a member of the Pleiades supercluster [Eggen 1995]. On the other side, the trailing edge of the burst of stars could be approaching the Pleiades. Such stars could be superposed on the cluster with respect to sky coordinates, would have similar space motions, and would seem to satisfy cluster membership criteria closely enough (if not perfectly). That is our explanation for the brighter lithium HHJ objects.

4 Conclusion

The discovery of BDs was the highlight of my astrophysical career. It is rare to find a whole new class of astronomical object, especially ones that are as much as a few percent as numerous as stars. Our motivations were several, including the joy of the hunt, the possibility that BDs were a significant component of dark matter (which turned out not to be the case), and the interest in observing objects intermediate between stars and planets. My involvement with BDs also led to very enjoyable participation in the debate over "what is a planet" (which examines both the low and high mass boundaries for planets). Obviously the discovery involved a lot of friends and collaborators, and I share the experience and credit with them. I was very fortunate in being a faculty member at UC Berkeley, where the Keck telescopes were conceived and where Keck access was possible early on. Astronomers at the Univ. of California and Caltech knew we had a unique opportunity to do important work with this new tool, and many epochal discoveries have been made utilizing it. We owe a debt to the designers and builders of the telescopes, and I especially want to thank Prof. Steven Vogt, who designed and built both the the high resolution

spectrographs that have enabled the bulk of the science that I have done. I also want to thank the organizers of the conference (especially Viki Joergens) who caused this book to be written. It was a pleasure to revisit those exciting days gone by, and to see the tremendous progress that has been made on BDs since then.

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