The Lithium Test for Young Brown Dwarfs

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Abstract.
I discuss the successful application of the "lithium test" to the problem of distinguishing young brown dwarfs from true stars, given that they occupy overlapping regions of effective temperature and luminosity. In simple terms, stars will burn lithium in at most 100 Myr, while brown dwarfs may never reach the core temperature required to do so. The minimum lithium burning mass is not the same as the minimum stellar mass however, introducing some subtleties into the the lithium test. I discuss the history of this subject, leading up to its successful application in the Pleiades. 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 proper usage of the lithium test itself. I also discuss how lithium observations of very cool objects can be useful in constraining the nature of brown dwarf candidates both in the field and in star forming regions.

1. Introduction

The search for brown dwarfs can be divided into three qualitatively different arenas. The most obvious is the search for old visible brown dwarfs, whose temperature and luminosity obviously lie below the minimum possible value for stars. This can be done by looking for stellar companions, or in the field. Only Gl 229B has been found in this category so far (Nakajima et al. 1995). Such objects are unambiguously brown dwarfs, with no further proof needed. There are several objects near the boundary, such as GD 165B (Becklin and Zuckerman 1988) and further candidates mentioned in this volume. More will certainly turn up in the many continuing searches for them.

The second arena is the dynamical brown dwarfs, where orbital information suggests a mass below the minimum stable hydrogen burning limit. Here one need not be able to actually see the brown dwarf; its effect on a stellar companion can reveal it. If the orbit is spatially resolved their actual masses can be found, otherwise only lower limits can be placed due to the unknown orbital inclination. There are no examples of unambiguous dynamical brown dwarfs at present. There are, however, ample discoveries of objects whose lower mass limit is comfortably in the brown dwarf regime (eg. Mayor et al. 1997). One cannot be certain of any individual case, but the statistics of these discoveries makes us sure that many of them are *bone fide* brown dwarfs (cf. Basri and Marcy 1997).

The third arena in which to search is for young brown dwarfs, which are visible and at their brightest. While these are the easiest to see, it is harder to be sure that they are really brown dwarfs. At early ages, the brown dwarfs occupy the same region of temperature and luminosity as very low mass (VLM) stars. One can trade off mass and age to infer either a brown dwarf or a star at a given observed value of L,T. For isolated objects in the field this is a particularly acute problem, since their age is not generally known. Even in a cluster, the mere fact that an object occupies a position in an HR or CM (color-magnitude) diagram where theory tells us to expect brown dwarfs at the age of the cluster has not proven convincing by itself. This is partly because the theory which converts observational quantities to L,T is still being refined, and partly because other factors may invalidate the conclusion. Among these are the possibility that the object may not actually be a member of the cluster, or that the age of the cluster may have a large spread or may not have been correctly determined.

We therefore would like a more direct test of the substellar status of a candidate before certifying it. Since the difference between brown dwarfs and stars lies in the nuclear behavior of their cores, it is natural to look for a nuclear test of substellar status. There is a relatively straightforward diagnostic which is fairly simple both theoretically and observationally: the "lithium test". This relies on the fact that even before hydrogen burning commences, core temperatures in a star reach values (about 2-4 MK) which cause lithium to be destroyed (Nelson et al. 1993). On the other hand, in most brown dwarfs the requisite core temperature is never reached because of core degeneracy, and lithium will not be destroyed. Furthermore, at masses near and below the substellar boundary, the objects are all fully convective so that surface material is efficiently mixed to 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. Thus, to zeroth order, a brown dwarf candidate in which lithium is absent is probably a star, while one in which it is present may be a brown dwarf. Complications to this are discussed in §3.

The exact position of the substellar boundary in mass, luminosity, or temperature, depends on the composition of the object and on not yet fully settled aspects of the theory of such objects. For our discussion, we adopt $75 M_J$ as the mass boundary, $10^{-4} L_\odot$ as the luminosity boundary, and an effective temperature of about 2000K. Note that these are the properties of the lowest mass star *when it reaches the main sequence* (which takes several Gyr). Before then, both stars and brown dwarfs can be hotter and brighter.

2. Early Applications of the Lithium Test

The idea behind the lithium test was implicit in calculations of the central temperature of low mass objects by D'Antona and Mazzitelli (1985) or Stringfellow (1989) and others. They found that the minimum lithium burning temperature was not reached in the cores of objects below about $60 M_J$ at any time in their evolution. On the other hand, it is known that no M stars on the main sequence have been observed to have retained their lithium. That the lithium resonance line should be easily observable in VLM objects was becoming increasingly clear by the time of Magazzù et al. (1991), who saw lithium in a very cool T Tauri star. Discussion between the IAC group and D'Antona's ensued. A formal proposal to use this line as a means of distinguishing 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 (and also the equivalent tests using beryllium and boron).

The theory of lithium depletion in VLM objects is comparitively simple. Because the objects are fully convective, their central temperature is simply related to their luminosity evolution. An analytic study of lithium depletion by Bildsten et al. (1997) is a particularly revealing exposition of the heart of the problem. The physical complications in VLM 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 VLM objects.

The lithium burning crossections are fairly secure, and the other input physics has converged sufficiently well that the basic timescales inferred are unlikely to change significantly in the future. Calculations supply the age and timescale of lithium depletion for objects above and below the substellar boundary. They provide the L,T at which an object of a given mass will lose its lithium, and the age to be inferred from a determination of the depletion boundary in L,T in a given cluster. One of the main deficiencies of the Nelson et al. (1993) treatment, the use of grey atmospheres, has been addressed by Chabrier et al. (1996), who also have updated opacities. Similar calculations are also being done by the Arizona group. They do not change the basic timescales found by Nelson et al., giving confidence that we are close to the final answers.

The other information needed to apply the test is what the strength of the lithium line will be for a star of a given temperature and lithium abundance. Such calculations depend partly on the atmospheric model, and partly on the lithium line formation. In both areas there has been substantial progress over the last few years. Work by Pavlenko et al. (1995) has concentrated on the lithium line at very cool temperatures. Their basic result, that the lithium line should be quite strong in the 2000K-3000K range, is confirmed both by other (unpublished) results from Hauschildt and Plez, and by the actual observations described below. NLTE effects and the effect of chromospheric activity have been considered by Pavlenko et al. and by Stuik et al. (1997), and found to be of secondary importance.

The strength of the line means that it does not begin to desaturate until more than 90% of the initial lithium has been depleted. The timescale during which the lithium line disappears is a few times 10 Myr, which is roughly 10-20% of the age at which it occurs in substellar objects. The details of the atmospheric structure of VLM stars are still changing with the ever improving opacities in the work of Allard (see this volume) and others; the latest wrinkle is the addition of dust opacities in very cool atmospheres. Thus we cannot consider the translation of a lithium equivalent width to abundance to be a fully settled issue, but the line is certainly expected to be present unless there is strong depletion.

Based on the clear possibility of using the lithium test to confirm substellar status, the group at IAC embarked on an effort to apply it to the best existing brown dwarf candidates, in the field, in binaries, and in clusters. They used 4-m class telescopes at spectral resolutions of 0.5Å for a brighter initial sample

(Magazzù et al. 1993) and 2-4Å (Martín et al. 1995). This latter resolution is lower than ideal, but the observations are very difficult due to the faintness of VLM objects. They were unable to detect lithium in any of the candidates. For most targets (since the ages aren't known) this implied a lower mass limit of more than 60M_J but did not resolve whether they are brown dwarfs. For the field objects, that was not inconsistent with other information on the objects. Had lithium been detected, it would have been strong evidence for substellar status. The negative results served to constrain the effective temperature calibration for VLM stars, and to dampen enthusiasm for the proposition that all stars M7-10 are really young brown dwarfs (eg. Kirkpatrick 1994).

The conclusions were different for their Pleiades candidates. These were drawn from the Hambly et al. (1993) list of very faint proper motion objects, and those authors had already suggested brown dwarf candidacy based on the L,T position of the objects compared to evolutionary tracks for the age of the Pleiades (thought to be 70 Myr). Martín et al. (1995) realized that there was an inconsistency between the inferred mass of these Pleiads and the lack of lithium. The situation was even worse with the results of Marcy et al. (1994), who observed a yet fainter Pleiad, HHJ 3, with better upper limits on the lithium line (due to their access to the newly commissioned Keck 10-m telescope). Both groups pointed out that the effective temperature scale for VLM objects was then known to have inconsistencies with the main sequence, and if the objects were really 200-300K hotter then they would have larger inferred masses and be expected to have lost their lithium. The situation at this point was reviewed by Rebolo et al. (1995a).

3. The First Lithium Brown Dwarfs

The first application of the lithium test to a brown dwarf candidate with a positive result came in the study of PPL 15 by Basri et al. (1996a; hereafter BMG). PPL 15 is an object only slightly fainter than HHJ 3, and was the faintest known Pleiad at the time of the study. It taxed even the Keck telescope (at high spectral resolution); more than a full Keck night of integration was devoted to the task. The result was that BMG reported the reappearence of lithium on the faint side of "lithium chasm" in the Pleiades. The strength of the line was apparently less than expected for undepleted lithium in an M6.5 star, based on high resolution model spectra. At the same time, BMG confirmed that PPL 15 had the right radial velocity and Hα strength to be a cluster member (it was discovered by J. Stauffer in a photometric, rather than proper motion survey).

BMG then had to explain how lithium could appear in PPL 15 but not in HHJ 3. As they are almost the same spectral type, a temperature error did not seem to provide the explanation. BMG did not rely on the temperature scale at all, but instead used a bolometric correction to convert directly to luminosity (eg. Tinney et al. 1995). This conversion was on a firmer empirical basis than the temperature scale (although there are still some problems with the conversions for IR vs. optical colors, and the temperature scale is now much improved). The solution to the problem becomes apparent in a luminosity-age diagram, with the lithium depletion region displayed (Fig. 1). The theory used in the Figures is a version of calculations by Chabrier and Baraffe from 1996. For example, with

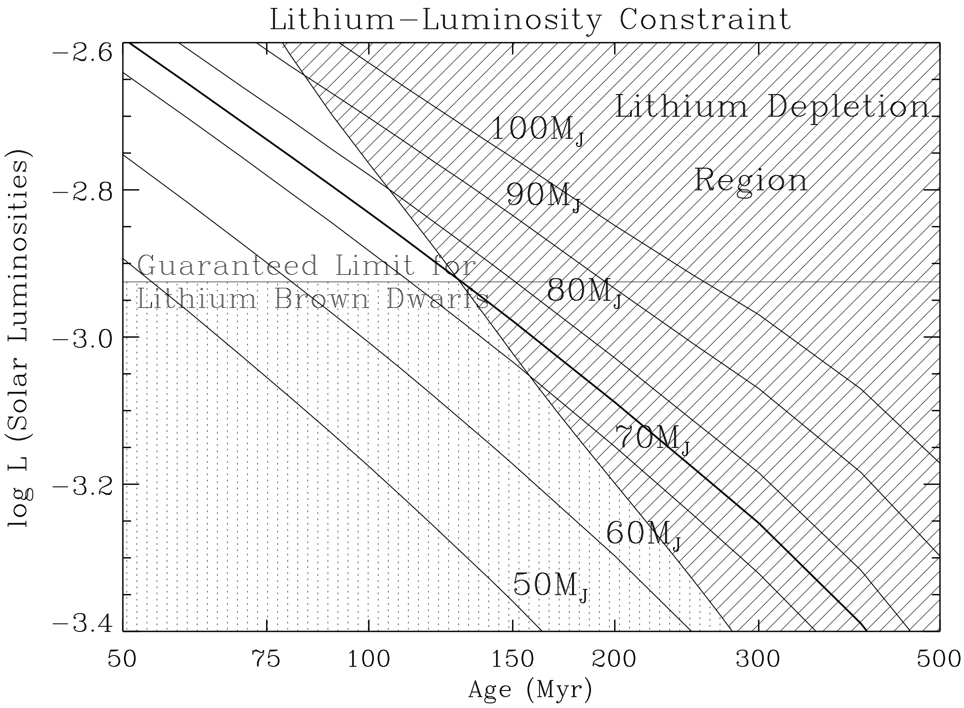

Figure 1. Figure 1. Lithium depletion in a luminosity-age diagram. Cooling curves are shown for several masses. The lithium depletion region (where lithium is reduced to 1% of its primordial value) is given by the hatched region. The region where a lithium detection guarantees a substellar object (regardless 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$_J$.

log(L/L$_\odot$) of -2.85 and no lithium seen, HHJ 3 must be at least 120 Myr old. PPL 15 is 0.1 dex fainter, and so can still have lithium at that age.

Fig. 1 shows that the lithium test is more subtle than presented in the Introduction. 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). Note, however, that there is no question about the mixing timescales for surface material to the core; this occurs rapidly compared to the depletion timescale, and completely. 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 brown dwarfs will deplete their lithium too (giving the possibility of a false negative in the test).

This highlights the fact that a common misconception about brown dwarfs, that they are objects without fusion, is not true. In fact all brown dwarfs above 12M$_J$ will experience deuterium fusion (Saumon et al. 1996), and brown dwarfs between about 60-75M$_J$ will also burn lithium (and even burn some hydrogen for a period of time). What makes them "substellar" is that they can never stabilize this way: they don't reach the main sequence. The presence of some fusion means that to properly apply the lithium test to brown dwarf candidates, knowledge of their age is very helpful. While it was thought that the ages of clusters like the Pleiades were known well enough for this purpose, that turns out not to have been the case.

BMG resolved the problem of the nondetection of lithium in HHJ 3 and its presence in PPL 15 by suggesting that the Pleiades is substantially older than previously thought. They showed that with an age of 120 Myr (rather than 75 Myr), the behavior of both stars makes sense (Fig. 1). I do not discuss the age issue further here; see BMG or my contribution to the 1997 Palermo Workshop on Open Clusters for further insight. Suffice it to say that there are good reasons from stellar evolution theory why the previous age could be so much in error. The reason that HHJ 3 is depleted is that its mass is substantially greater than implied by its observed luminosity and the younger age – high enough to make it a star rather than a brown dwarf. The inferred mass of PPL 15 is thereby also raised, to just about the substellar boundary. It could be in the process of depleting lithium now, explaining how two such similar stars can show different lithium abundances.

The suggested increase in age puts the Pleiades very close to the age where the lithium test actually separates stellar from substellar objects (despite the subtleties above). A recent footnote is that PPL 15 appears to actually be a binary (Basri and Martín, this volume). Its individual components are therefore less luminous and massive than previously thought, and the lithium boundary may not be quite so near to HHJ 3. Further observations of objects between HHJ 3 and PPL 15 are called for. Furthermore, the distance to the Pleiades found by Hipparchos yields fainter inferred luminosities by nearly 10%. As the boundary gets fainter, the age goes up. In any case, the prediction was that any Pleiads found that are fainter than PPL 15 should show strong lithium.

This prediction was tested in short order. Rebolo et al. (1995b) announced the discovery of Teide 1, a fainter M8 Pleiad with apparently good cluster membership credentials. Observation of lithium in this object is strong confirmation of the lithium boundary in the Pleiades. Field M8 stars are quite unlikely to be young enough to show lithium, and obviously brighter Pleiads have already depleted it. This candidate is too faint to do with HIRES on Keck, but being cooler its lithium line should grow strong enough to be seen at lower dispersion. Rebolo et al. (1996) used the LRIS at Keck to confirm strong lithium in both Teide 1 and a very similar object: Calar 3. As these are well below PPL 15 in L,T they must be considered ironclad brown dwarfs in the cluster. They have masses in the range 55-60M_J using the BMG age for the cluster; these masses would be substantially *lower* using the canonical age. Several other interesting photometric candidates turned out not to have the right radial velocity or color (Martín et al. 1996); we have confirmed that Calar 1 shows no lithium.

As discussed elsewhere in this volume (Zapatero-Osorio), the IAC group has now found a large number of Pleiades brown dwarf candidates (selected photometrically), extending down to inferred masses as low as about 30M_J . Having successfully applied the lithium test to this cluster to determine the L,T of the substellar boundary, it is no longer necessary to test all these candidates for lithium. Establishment of cluster membership for objects faintward of the boundary is sufficient proof that they too are brown dwarfs. This can be done with proper motion, radial velocity, and perhaps Hα and rotational data. The more of these used, the better. We must be cautious about Hα, given that Basri et al. (1996b) find that the usual connection between rotation and activity has broken down in field late M stars. The behavior of young cluster stars later than M6 in this context is not yet firmly established. Observation of lithium in the brighter brown dwarf candidates certainly helps the case for membership (and directly proves substellar status).

4. Wider Use of the Lithium Test

Can we build on the initial successes in the Pleiades? The next obvious step is to go to other clusters younger than 1 Gyr and try to locate the lithium boundary. The most obvious examples to try next are the Hyades (600 Myr), Praesepe (400 Myr), and α Per (50 Myr). Of course, these ages are the canonical ones, and the clusters may well be 50% or more older. As a cluster ages, the luminosity of the lithium depletion boundary gets fainter. Thus, while it is helpful that the Hyades is one-third the distance of the Pleiades, the lithium boundary will be at fainter apparent magnitudes. By the same token, while α Per is further away, its youth means that the apparent magnitude of the substellar boundary should be similar to the Pleiades. Praesepe will clearly be more difficult. There are some clusters in the southern hemisphere which are also promising. This work will also help confirm whether the cluster age scale really needs the revision implied by the Pleiades.

The steps to be followed are first to conduct photometric surveys similar to the very successful work at the IAC. New large format cameras will speed this process. Once candidates are found in the appropriate part of the CM diagram, low dispersion spectroscopy can confirm whether they are late-type dwarfs and have reasonable values of radial velocity and Hα. Then one must work faintward at higher dispersion, looking for the re-emergence of lithium. Once the lithium boundary for a cluster is firmly established, the work can proceed to fainter levels only using cluster membership as a criterion. Thus, proper motion work at very faint magnitudes should be conducted concurrently, to provide final confirmation of cluster membership.

Note that the luminosity of the lithium depletion boundary has its primary utility as a nuclear age calibrator. The luminosity of the substellar boundary at that age can then be inferred from depletion and cooling theory, and will not in general be coincident with the depletion boundary. The long term goal of searching for brown dwarfs in clusters is to discover whether there is a "universal" substellar mass function among clusters (or what variations there are, and why). In doing this, one must correct for unseen binaries (and stripping of wide binaries) and for mass segregation (and eventual evaporation) of low mass members caused by the cluster environment.

4.1. Field Objects

Can the lithium test be used for field objects? The problem, of course, is that one will not generally know the age. Still, the lithium test does provide good joint constraints on the mass and age. Figure 1 shows that the lithium depletion region, taken with the observed luminosity of the object, provides a lower bound to the mass and age of the object if lithium is not seen. Conversely it provides a upper bound to the mass and age if lithium is seen. Thus, observation of lithium in a field object can constrain it to be a brown dwarf if the object is faint enough. For example, if the luminosity of the object 269A (Thackrah et al. 1997) is slightly less than $10^{-3}L_\odot$ (the "guaranteed limit" in Fig. 1) then it is a brown dwarf, since lithium has been seen in it. That is because no star can become that faint without having depleted lithium. Its confirmation therefore, is a matter of establishing a good parallax. By similar reasoning, Teide 1 and Calar 3 are brown dwarfs even if they were not Pleiades members.

For the objects of Hawkins et al. (1996), the originally suggested luminosities were around $10^{-4}L_\odot$. Thus, if they show lithium, they are definitely brown dwarfs. On the other hand, if they don't show lithium they could still be brown dwarfs with masses between 65-75M_J and sufficiently old ages. Finally, if they are found to be below $10^{-4}L_\odot$, then they are brown dwarfs independent of the lithium observation. Similar considerations apply to all the newly discovered very faint and cool field objects (like KELU-1; Ruiz 1997). It therefore still makes sense to conduct the lithium test on field objects. It is not as definitive as in clusters, but can provide firm confirmation under some conditions.

4.2. Star Forming Regions

The lithium test is even less obviously useful in star forming regions (SFR). Here none of the objects have had time to deplete lithium yet, even rather massive stars. Nonetheless, there have been a spate of reports of brown dwarfs in SFR, including Taurus (Briceno et al., this volume), ρ Oph (Williams et al. 1995), and Orion (Hillenbrand 1997). These are identified as brown dwarfs on the basis of their position in CM or HR diagrams, using pre-main sequence evolutionary tracks. The state of this theory is not yet fully satisfactory for this purpose, although the fainter of the objects are very likely to be substellar. It would be very nice to have an independent way to confirm their status. As yet none have been found in systems that could yield a dynamical mass test.

It turns out that lithium observations have a role to play even here. One obvious point is that if one observes one of these candidates and it doesn't show lithium, it can be eliminated immediately as being a non-member of the SFR. It turns out, however, that there is another constraint one can place on the substellar objects with sufficiently low mass, which constitutes a confirmation of their substellar status (independent of whether they are really in the SFR or not). One can study the temperature vs. age for objects of various masses, and determine when each of them will deplete lithium. This is shown in Fig. 2. The temperature at which the highest mass brown dwarf depletes lithium sets a maximum below which, if lithium is observed, the object must automatically be substellar. More massive objects will have destroyed lithium before they can cool to this temperature.

A substellar limit of 75M_J implies a temperature limit of about 2700K, which roughly corresponds to a spectral type of M6 (Baraffe and Chabrier 1996). Thus, *any object M7 or later which shows lithium must be substellar.* This holds regardless of its luminosity or age, and therefore constitutes a proper lithium test

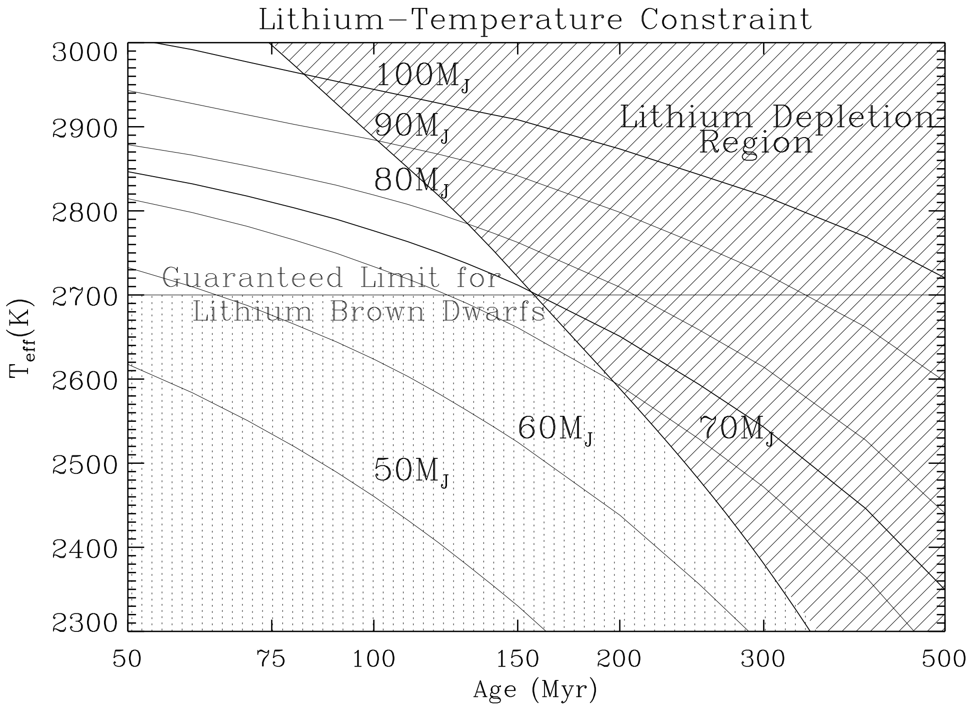

Figure 2. Lithium depletion in a temperature-age diagram, quite similar to Fig. 1. The lithium depletion region (where lithium is reduced to 1% of its primordial value) is given by the hatched region. The region where a lithium detection guarantees a substellar object (regardless of age) is shown with 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 .

even in SFR. This test is preferable to the analogous luminosity limit because determination of spectral type is not sensitive to the large range of extinctions found in SFR (which do affect luminosity estimates). Of course, objects below the "guaranteed limit" at the age of SFR are really rather low mass brown dwarfs (Fig. 2). Many other more massive brown dwarfs in the SFR will elude confirmation by this test. It can inspire confidence, however, in the measurement of the substellar mass function at its lower end in SFR.

Lithium is a very useful diagnostic of the state of very low mass, very cool stellar and substellar objects. With a little care, the lithium test is a powerful means of constraining mass and age, given a luminosity or temperature. It is capable of certifying appropriate objects as substellar beyond a reasonable doubt. While there are a number of theoretical issues which need refinement, the basic idea behind the test is quite robust, and it is quite powerful even in its simplest form (lithium vs. no lithium). The lithium test will surely continue to play a major role in the study of young VLM stars and brown dwarfs.

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