Lithium near the Substellar Boundary: A New Age Diagnostic

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ABSTRACT.
I discuss some of the most interesting results to come out of high resolution spectroscopy with the Keck telescope on very faint members of the Pleiades cluster. The first is the detection of the cool side of the "lithium chasm", in which lithium is completely depleted by burning in the stellar interiors. On this side of the chasm, at the age of the Pleiades, one finds brown dwarfs. That is not the main point of interest here, however. Rather I focus on the age of the cluster implied by these observations. It is nearly twice the canonical age of 75 Myr. I argue that the lithium age is more reliable, and that there is a general problem in the dating of young open clusters. We have preliminary evidence of the same problem in the α Per cluster. It can be explained as due to convective core overshoot in the massive stars which were used to produce the classical ages. Finally, I offer a caution on inferred age spreads in young clusters.

1. Introduction

Examining the cosmic abundances of the elements, one is immediately struck by the huge deficit of the light elements between helium and carbon. Lithium, beryllium, and boron are all fragile nuclei, easily "burned" when fusion is occurring. Before the conditions for hydrogen burning are reached (though after deuterium is burned), lithium will combine with a proton and break up into helium. One benefit is that lithium can provide both a stellar interior thermometer and a clock, since the time required to reach these conditions and then deplete the lithium is calculable. A diagram of lithium abundance vs. mass for a cluster can show a lithium "chasm" in which no surface lithium is detectable, with steep walls on both sides. We give it this name to distinguish it from the more modest lithium "Boesgard gap" which occurs in the F spectral range (for non-classical reasons). On the hot side of the chasm (G,K stars), the decline and disappearance of lithium is already well studied. On the cool side lithium should still be present because low mass objects have not been able to accomplish lithium depletion due to their low interior temperatures and slow evolutionary timescales.

The study of lithium depletion in stars has kept astrophysicists amused for some decades. Of course, we can only determine if the *surface* lithium is depleted. The question of surface depletion depends on whether surface material is mixed down to the burning zone in a star. Stars tend to be born fully convective, in which case the surface material is mixed throughout the star on timescales short compared with evolutionary times. There ensues a race between the retreat of the convection zone to cooler heights, and the rising temperature in the core. It is the history of the temperature at the bottom of the convection zone which determines if and when surface lithium will disappear.

In a solar-type star, the convection zone retreats fast enough to preserve much of the lithium during the pre-main sequence phase. The Sun has, however, lost most of its lithium while on the main sequence. The mechanisms by which this happens are not fully understood, and the subject of lithium depletion in partially convective stars is in continuing debate (Martín, this volume). Happily, one can avoid non-classical mixing mechanisms by considering stars which remain fully convective even on the main sequence. At masses below about $0.3M_{\odot}$, or main sequence spectral types later than about M3, that will be the case. The structure of such stars remains close to simple polytropes, and the history of the central temperature is governed by standard physics. Bildsten et al. (1997) have shown that using analytic approximations, one can come close to the lithium depletion results from sophisticated numerical codes.

2. The "Lithium Chasm" in the Pleiades

The site where the lithium clock was first employed is the Pleiades open cluster. This cluster received intense scrutiny because it was a likely site to consummate the search for young brown dwarfs. It is relatively close by (120 pc) and its age of 75 Myr as determined by standard calculations of its upper main sequence turnoff (UMST) leaves the high mass end of brown dwarfs in the M5-M6 spectral range. Furthermore, the lithium test for brown dwarfs as proposed by Rebolo et al. (1992) could be easily applied to this cluster (cf. Basri 1997). It was expected, however, that the faintest objects discovered by the survey of Hambly et al. (1991; HHJ) should both show lithium and be brown dwarfs given a cluster age of 75 Myr. Searches for lithium in these objects did not find it (Martín et al. 1994), even in the faintest one (HHJ 3) tested at high resolution with the newly commissioned Keck telescope (Marcy et al. 1994).

Finally Basri et al. (1996; BMG) detected lithium in the M6.5 object PPL 15, which had been discovered by Stauffer et al. (1994). PPL 15 is fairly close in luminosity to HHJ 3 because of the steepness of the cool wall of the lithium chasm. This places a tight contstraint on the age of the cluster (see next section). That age is in the range of 120-130 Myr, substantially greater than the UMST age. It implies larger masses at a given luminosity (since low mass objects will have had longer to fade). It is of interest that the inferred mass of PPL 15 even after this adjustment is at the substellar boundary, making PPL 15 the first "lithium brown dwarf".

PPL 15 turns out to be a spectroscopic binary (Basri & Martín 1997), which makes each of the components about a factor of 2 fainter. Furthermore, the new Hipparcos distance to the Pleiades is about 10% less than previously thought, which would further reduce the implied luminosities. Thus the lithium boundary could be more than a magnitude below where BMG thought it was. This only makes their conclusions even more striking (each component of PPL 15 is more definitely a brown dwarf, and the age discrepancy implied could be even larger). Brown dwarfs are not the subject of this paper (see the March 1997 Tenerife conference on "Brown Dwarfs and Extrasolar Planets" for an excellent current review of that subject). The luminosity of the boundary should be refined by testing new candidates fainter than HHJ 3 for lithium, regardless of their substellar status.

3. Ages of Young Clusters

The idea of lithium dating was mentioned in passing by D'Antona and Mazzitelli (1994). It received its first real application in the Pleiades by BMG, who independently conceived it to solve the dilemma of HHJ 3/PPL 15. In its simplest form, the method is simply to observationally determine the luminosity of the faint edge of the lithium chasm. One needs spectroscopy at 670 nm with sufficient resolution to observe the lithium resonance line (detecting an equivalent width of .25-.5Å is desirable). For this purpose it is not necessary that a conversion between lithium line strength and lithium abundance be made. One must also be able to assign a bolometric luminosity or effective temperature to a star. Calibrations have to be known throughout the M spectral range. Further work on this is needed, particularly on the question of differences between the main sequence and the pre-main sequence.

The theory required to apply lithium dating is the evolution of the central temperature of fully convective pre-main sequence stars (Fig. 1). The agents producing luminosity in these objects are gravitational contraction, and early on, deuterium burning. The object evolves according to how rapidly it radiates this luminosity away, which depends on its surface opacity. Although low mass objects are cool and therefore have complex molecular surface opacities, the central temperature doesn't depend on the details of the surface opacity but on how much radiation escapes over all wavelengths. Modern opacity tables are also becoming good enough to match spectra in detail (Allard et al. 1997).

A number of authors have performed very sophisticated calculations of lithium depletion in low mass stars. These include Nelson et al. (1993), D'Antona & Mazzitelli (1994), Chabrier et al. (1996), and Burrows et al. (1997). These differ in the details of the opacities used and the approximations in the treatment of the atmospheres (LTE/NLTE, grey/non-grey, dust?) and the interior equation of state. The depletion of lithium is rapid compared to the age at which it occurs, so the particulars of the depletion are of secondary importance. The timescales and luminosities from various groups agree with each other well enough to provide a clock with about 10% accuracy, which is rooted in simple and fundamental stellar evolutionary theory.

The discussions in Bildsten et al. (1997) and Ushomirsky et al. (1998) are excellent summaries of the important physical considerations and questions. There is a direct relation between the effective temperature of an object and its lithium depletion timescale, so in principle it is best to use the effective temperature to define a lithium depletion age. Operationally this may also seem preferable, since only spectroscopic observations are needed to employ a depletion diagram like that in Fig. 1. However, the relations between effective temperature and observables (eg. color) are still somewhat unsettled in very cool stars (though again the agreement between models and observations is rapidly converging). These concerns can be somewhat ameliorated by using instead the luminosity at which a star will deplete its lithium (relying on empirically calibrated bolometric corrections), as done by BMG.

The ages which can be determined by the lithium depletion time range in principle from around 10 Myr up to nearly 1 Gyr. At earlier times the stars have not had sufficient time to deplete lithium, while later than this the lowest mass object which

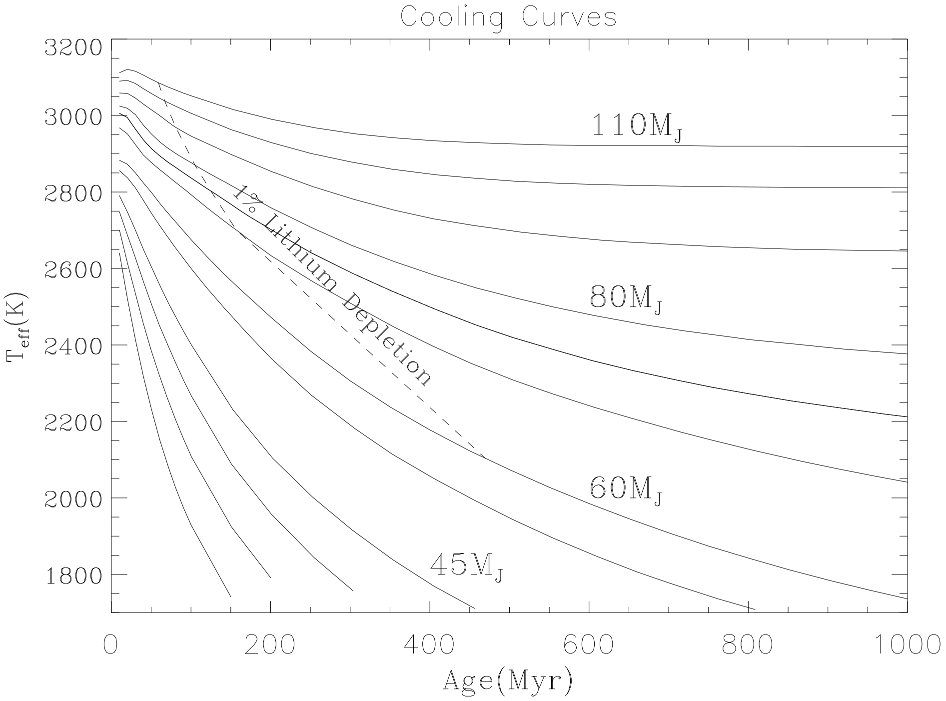

Fig. 1. Theoretical models for objects near the substellar boundary, from recent calculations by Baraffe and Chabrier. Shown is the T_{eff} behavior of the objects for the first Gyr. Also shown is a line to the right of which less than 1% of primordial lithium will remain. The masses shown are 110, 100, 90, 80, 75, 70, 60, 50, 45, 40, 35, and $30M_J$. $75M_J$ is the dividing line between stars and brown dwarfs.

can deplete lithium will have done so. Further lithium evolution can occur; we know that main sequence depletion takes place in solar-type stars (Martín, this volume). But the simplicity of lithium depletion in fully convective stars is lost. Thus, the method is useful now only on the cool side of the lithium chasm, while the hot side of the chasm is still plagued by our ignorance.

Although the UMST method of dating has a long history and is firmly entrenched in the minds of astrophysicists, it is not obviously preferable. For many of the young clusters (which are not nearly as rich as globular clusters), the number of UMST stars is low and defining the turnoff luminosity cannot be done with precision. More seriously, in the age range considered here (less than 1 Gyr), the UMST stars have convective nuclear burning cores surrounded by radiative envelopes. This yields a situation not unlike the lithium depletion uncertainty for solar-type stars: non-classical mixing can play a crucial role in the calibration of the age scale.

In particular, convective overshoot at the outer edge of the core can mix in unburned hydrogen, making the fuel supply larger. Depending on the extent of the mixing, this extends the age of the main sequence, and consequently the UMST age inferred at a turnoff of a given luminosity. I discuss current tests of convective overshoot in the next subsection, which have so far been somewhat inconclusive. The current consensus is toward values for the overshoot parameter that are probably insufficient to equalize the UMST and lithium depletion ages. I argue that the uncertainties associated with convective overshoot in UMST stars are more worrisome than problems with the calculation of lithium depletion ages in fully convective stars. Thus, the apparent age discrepancy in the Pleiades must be taken seriously.

One way to become more convinced that there really is a problem is to find the cool lithium depletion chasm wall in other young clusters. This requires a concerted effort to locate very faint, cool members of other clusters, and then to measure lithium in them. Fortunately this same program is required to study the substellar mass function in clusters, and is already underway. There are early indications of an age discrepancy in the α Per cluster. The lowest luminosity member checked for lithium (Zapatero et al. 1996) is of a luminosity where lithium is expected for the classical UMST age of α Per of 50-55 Myr. We have recently reobserved this star with Keck and improved the upper limit on the lithium line. Lithium is clearly not present. From this star the lower limit on the lithium age is 65 Myr (cf. Ushomirsky et al. 1998), and I emphasize that the lithium boundary has not yet been found. As we push to fainter objects, the inferred age will grow.

3.1. Convective Overshoot in UMST Stars

The issue of whether convective overshoot from the nuclear burning cores in massive stars occurs at a meaningful level, and if so how to treat it in stellar models, has bedeviled astrophysicists for more than a decade. Until then it was ignored, in particular in all the canonical age determinations of nearby young clusters. Those doing models today are well aware of the problem. It is clear that if there is convective overshoot, it will increase the age of a cluster when inferred from UMST stars sufficiently massive. In practice, this means that clusters whose ages are less than about 2 Gyr will be older than their classical ages if this effect is important. For older clusters, the turnoff stars are sufficiently low in mass (below about 1.4 $M_{\odot}$) that the correction becomes small or negligible. The amount of the effect can be seen in, for example, the set of models by Meynet et al. (1993). In that paper an age for the Pleiades of 100 Myr is found with an overshoot of 0.2 (the fraction of a pressure scale height into the stable region assumed to be mixed by overshooting).

There are a variety of tests which can be applied in stellar evolution theory to try to discover how much overshooting is implied by cluster CM or HR diagrams. The behavior of stars as they turn off the main sequence is different with or without overshoot. The behavior of red giants or supergiants will also be influenced by their larger helium cores if overshoot has occurred. The blue limit of the turnoff, the magnitude of the turnoff relative to main sequence stars, the brightness of the turnoff relative to red clump stars, the color of the clump stars, and other morphological features of HR diagrams all provide tests. One cannot directly use the change in inferred age of the cluster as a diagnostic of overshoot unless an independent means of determining the age is at hand. The lithium clock provides one; white dwarf cooling curves can provide another (Reid 1996).

Unfortunately, the various attempts to determine the amount of overshoot have thus far not been conclusive. Some recent papers using cluster CM diagrams are those of Daniel et al. (1994), Demarque et al. (1994), and Kozhurina-Platais et al. (1997). These have an unfortunate tendency to study clusters 1.5-2 Gyr old, where the effects of convective overshoot begin to diminish. Nonetheless, they generally conclude that a modest amount, say 0.2, provides better fits to the CM diagrams. Another method is to try to resolve the long-standing "mass discrepancy " in Cepheids with convective overshoot. Recent papers on this include Bohm-Vitense et al. (1997) and Wood et al. (1997). These stars are similar in mass to the UMST stars in the Pleiades. Both papers find that an overshoot parameter of 0.9 is needed to bring models (including pulsational information) in agreement with a precise independent mass determination. This value is close to what was used by Mazzei & Pigatto (1988) to infer an age for the Pleiades that is in excess of even the lithium age found by BMG.

A somewhat contrary view has been expounded by Stothers (1991) and Stothers and Chin (1992). These authors use a variety of tests, some fairly independent of each other, to deduce that there is no particular need for any convective overshoot to be included in models. They do not claim that there is in fact no overshoot, just that there is not a good case for it in their diagnostics. They do feel that the tests place an upper limit of 0.2-0.4 on the overshoot parameter. In all cases the models are subject to uncertainties in interior opacities and in the way in which convection and overshooting is treated. Thus, we are still in the unsatisfying position of not really knowing how much overshoot there really is, or how exactly to deal with it. I am not an expert in these matters; see the papers in this volume by D'Antona and Straneiro for further comments.

The method of lithium dating could be used to calibrate convective overshoot in UMST stars where overshoot is important. Once convinced that the physics of the low mass stars is more reliable, one could determine the lithium ages for various clusters. The amount of convective overshoot required to bring the UMST age into agreement with the lithium age can then be modeled, yielding an empirically determined overshoot parameter. We might still have to resolve why the tests mentioned above do not give a large value for it (because the currently preferred value of 0.2 for this parameter will not solve the Pleiades age discrepancy). It remains to be seen whether this discrepancy is typical or not.

4. How Coeval are Clusters?

For the Pleiades, there is a long history of discussion of various age spreads. In particular, there has long been a worrisome tendency for the lower mass stars to appear to be older than the UMST stars. Recent discussions of this problem in the Pleiades can be found in Stauffer et al. (1994) and Steele & Jameson (1995). The latter authors show that much of the spread of the stars off the ZAMS in a color-magnitude diagram can be ascribed to binaries. Stauffer et al. (1998) have also argued that part of the problem is in the stellar models and conversion of theoretical tracks to observational diagrams. Unless one is careful to choose a consistent set of models and calibrations, it is easy to infer an age spread (usually mass dependent) which is a result of systematic errors in the production of the CM or HR diagram.

It is not clear how large an age spread one should expect in an open cluster. Star formation histories for the nearby star-forming regions usually suggest a recent burst of formation (in the last few million years), with a tail of older stars in the cluster that may extend a few tens of millions of years. The lifetime of star-forming molecular clouds is thought to be in the range of 20-50 Myr (less near high mass star formation). It is not clear that this timescale is the appropriate one for bound open clusters. I want to urge caution about these extended tails of star formation. We may be detecting a population of stars which have wandered "into" the cluster' but were formed some time ago in another region. I don't think it is excluded that the typical cluster formation time is less than 10 Myr, though this is not established either.

I illustrate my point from a recent study by Oppenheimer et al. (1997; OBNK) of 2 pre-main sequence stars "in" the Pleiades. These have both proper motion and radial velocities consistent with cluster membership. Equally important is the assumption that they are at the cluster distance, which implies their pre-main sequence position in the CM diagram. In that case, they should be young enough to not yet have depleted lithium; OBNK find strong lithium in both (along with the expected Hα emission and rapid rotation). Thus, they pass all current possible tests for cluster membership. The presence of lithium means that their lithium ages are certainly less than about 25 Myr. Since the lithium age of the other low mass Pleiades is 100 Myr or more, one is forced to suppose that either the cluster has been producing stars for nearly 100 Myr or that their apparent membership is not valid.

OBNK point out that stellar kinematics can play an important role in where a star is found over a period of a few tens of Myr. It is not unreasonable, based on measured cluster velocity dispersions and molecular cloud turbulent velocities, to imagine velocity dispersions of 1-2 km/s for unbound stars. In 20 Myr they could move 20-40 pc from their birthplace. Thus, the fact that a 20 Myr-old star is found spatially coincident with a cluster (which is also moving), with a space velocity consistent with the cluster's to within 5 km/s, in no way guarantees that it is actually a member. OBNK construct a scenario in which recent star formation between us and the cluster could have formed stars which one would now find "in" the cluster. Indeed, Eggen's "Pleiades supercluster" could be the dispersed remains of such events. The large number of ZAMS and younger stars found in the RASS survey could also be members of this and other recently formed but dispersed populations. They will "pollute" the age distributions of nearby clusters, especially those projected on Gould's belt.

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