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Lithium in brown dwarfs

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Abstract. Lithium is a key element to establish the substellar nature of brown dwarf candidates. Theoretical calculations show that brown dwarfs with masses below ~ 0.065 $M_\odot$ preserve a significant fraction of their initial Li content while for higher masses total Li depletion occurs in short timescales. Lithium is preserved at masses well below the hydrogen burning mass. Strong lithium lines have been predicted and discovered in the spectra of brown dwarfs. Most of the bona fide brown dwarfs detected in stellar clusters and in the solar neighborhood have been confirmed to be substellar via detection of the lithium resonance doublet at 670.8 nm. I review these detections and the progress made in understanding the formation of Li lines in very cool high gravity dwarfs.

1. Introduction

Lithium is a well known tracer of stellar structure and a sensitive indicator of mixing processes in stellar interiors. As we move towards the bottom of the Main Sequence stars become more efficient destroyers of this fragile element. Observations in M-type stars of young clusters like α Persei and the Pleiades (see e.g. García López et al. 1994) show how the content of lithium is significantly reduced after several tens of Myr. This depletion is explained in terms of nuclear burning via the reaction ^{7}Li(p,α)^{4}He which is very efficient at temperatures above $\sim$2.4 10^6 K. Such temperatures are easily attained in stellar interiors, but never reached in less massive objects like brown dwarfs or giant planets. Brown dwarfs are gaseous bodies with insufficient mass to produce stable hydrogen burning, they are less massive than 0.075 $M_\odot$ and are expected to form, as stars, from the direct collapse and fragmentation of molecular clouds. A comprehensive description of the theoretical properties of these fully convective objects can be found for instance in Burrows and Liebert (1993) and Chabrier et al. (2000). Brown dwarfs were first conceived by Kumar 1963, but their existence was not proved until 1995 with the discoveries of a young hot brown dwarf in the Pleiades star cluster (Teide 1, Rebolo et al. 1995) and a cool "methane" brown dwarf around a nearby M-type star (Gl 229 B, Nakajima et al. 1995). Since then, several hundreds of potential brown dwarfs have been identified in stellar clusters (see e.g. Zapatero-Osorio et al. 1997, Luhman et al. 1997, Bouvier et al. 1998, Béjar et al. 1999) and in the solar neighborhood (Ruiz et al. 1997, Delfosse et al.

1997, Kirkpatrick et al. 1999). Here I review the crucial role played by lithium in our understanding of this fascinating new class of astronomical objects.

2. The lithium test

Models describing the interiors of brown dwarfs predict the evolution of their core temperatures as a function of time. From the early work by D'Antona and Mazzitelli (1985), it was already possible to realize that below a certain mass, brown dwarfs will never reach a core temperature sufficiently high to produce lithium burning. Opposite to very low-mass stars, these brown dwarfs can preserve the original content of lithium (see e.g. Stringfellow 1989; Pozio 1991). Ten years ago, the effective atmospheric temperatures of objects close to the substellar limit were subject of controversy and difficult to predict on theoretical grounds. The available spectral type-T_{eff} calibrations appeared to indicate that brown dwarfs could have effective temperatures slightly lower than those of the coolest T Tauri stars with detected Li. These considerations prompted Rebolo Martín and Magazzú (1992) to compute the formation of the Li I resonance doublet at 670.8 nm using Allard (1990) model atmospheres with T_{eff} in the range 2000 to 2700 K. The computations showed the formation of a very strong line (equivalent width of several Å) in such cool atmospheres and led to propose a spectroscopic test based on its detection as a powerful tool to confirm the substellar nature of brown dwarf candidates: the Li test. This was presented in more detail by Magazzù, Martín and Rebolo (1993) who also reported on the first search for lithium in several of the best brown dwarf candidates known at that time. The evolution of the lithium abundance in very low-mass stars and brown dwarfs was later extensively considered in several works which reported remarkable agreement on the timescale for lithium depletion and the minimum mass for lithium preservation (see e.g. Nelson, Rappaport and Chiang 1993; D'Antona and Mazzitelli 1994; Chabrier, Baraffe and Plez 1996). This agreement is achieved in spite of the use of different interior models, equations of state, screening factors for nuclear reactions or atmospheric opacities, basically reflecting the little sensitivity to these parameters of the core temperatures as a function of time, and the robustness of the predictions regarding lithium. In Fig. 1 we plot lithium depletion curves obtained with the NextGen models by Chabrier et al. (1996). It is obvious from the figure that brown dwarfs with masses below 0.06 $M_{\odot}$ preserve a significant (detectable) amount of lithium, and that below 0.05 $M_{\odot}$ lithium is fully preserved. The mass limit for Li preservation is clearly below the substellar mass limit, usually accepted to lay between 0.08 and 0.07 $M_{\odot}$ for solar metallicity. The shape of the destruction curves also predict a sharp transition between Li-poor and Li-rich objects at the bottom of the main sequence of a cluster like the Pleiades.

3. Detection of lithium in brown dwarfs

The first searches for lihium in brown dwarf candidates gave negative results (Magazzù et al. 1993; Martín, Rebolo and Magazù 1994; Marcy, Basri and Graham 1994). Nearby late M-type dwarfs (GL 234 B, GL 473AB, GL 569B, LHS 2924, etc) and the faintest proper motion objects discovered in the Pleiades

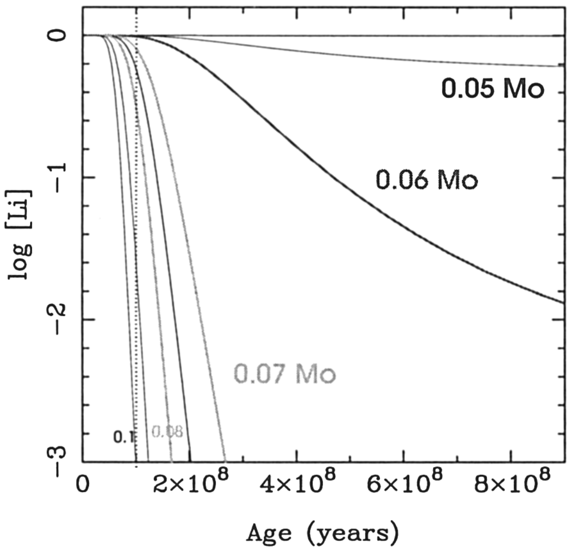

Figure 1. The evolution of lithium abundance as a function of time in very low mass stars and brown dwarfs.

cluster (like HHJ 10, HHJ 3 from Hambly et al. 1993) did not show lithium in their atmospheres. For the field objects with unknown ages the strong depletion of lithium just implied masses above 0.065 $M_\odot$, but the conclusions regarding substellar nature were much drastic for the Pleiades objects. Since at the age of the cluster ($\sim$ 100 Myr) a detectable amount of lithium was expected in objects with 0.08 $M_\odot$ or less (see Fig. 1), the depletion inferred from the observations clearly excluded the substellar nature of the examined Pleiads.

3.1. Brown dwarfs in stellar clusters

The first positive result of the lithium test was achieved by Basri et al. (1996) in PPl 15, an M6.5 dwarf in the Pleiades cluster discovered by Stauffer et al. (1994). The detection of lithium in PPl 15 put on empirical grounds the theoretical views on the reappearance of lithium at the bottom of the Main Sequence, but was not sufficient to establish the brown dwarf nature of this candidate which according to its effective temperature, luminosity and lithium abundance laid precisely on the boundary between stars and brown dwarfs. Uncertainties in these parameters, in the age of the cluster and in the theoretical timescales for lithium depletion prevented to conclude whether PPl 15 was stellar or substellar. The discovery of a fainter and cooler (M8 spectral type) proper motion member of the Pleiades (Teide 1) claimed to be a brown dwarf by Rebolo, Zapatero-Osorio and Martín (1995) offered a new extremely interesting opportunity to search for lithium in the substellar domain. Rebolo et al. (1996) reported the detection of a strong lithium doublet (EW$\sim$ 1 Å) in this brown dwarf and in the twin object Calar 3 (Martín, Rebolo and Zapatero-Osorio 1996). Estimates of the lithium abundances for these three objects can be seen in Fig. 2. After these discoveries many new brown dwarf candidates have been detected in the

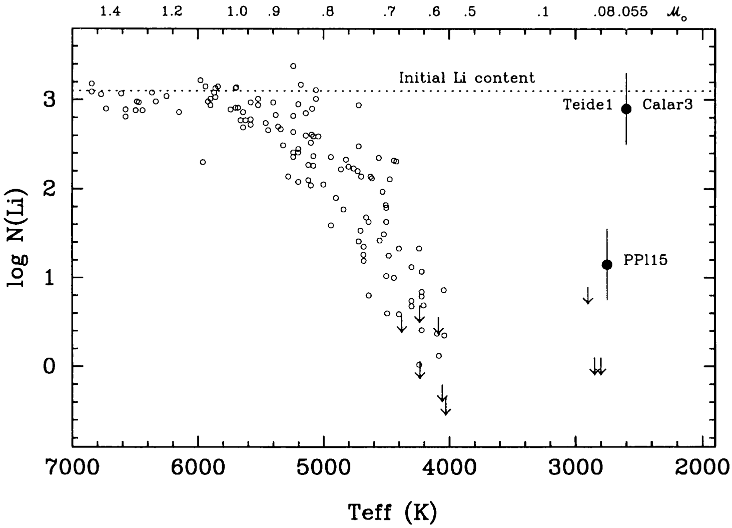

Figure 2. Lithium abundances versus effective temperatures for Pleiades F-M stars and first brown dwarfs (after Rebolo et al. 1996). Abundances are given in the usual scale log $N(H) = 12$.

Pleiades (Zapatero-Osorio et al. 1997, Bouvier et al. 1998) and new lithium detections have been performed beyond the stellar/substellar boundary (Martín et al. 1998, Stauffer, Schultz and Kirkpatrick 1998). These new observations confirm that there is an abrupt reappearance of lithium at the bottom of the Pleiades Main Sequence locating the edge of the lithium depletion at spectral type M6.5 and visual magnitude $I_c = 17.8 \pm 0.1$.

According to evolutionary models this depletion boundary is very sensitive to the age of the cluster and provides an effective method to estimate its age. The most accurate age determination for the Pleiades gives 125 ± 8 Myr (Stauffer et al. 1998), a value much higher than that derived from the upper main sequence turnoff of the cluster.

The lithium depletion boundary (LDB) has been determined in two more stellar clusters: αPersei (Stauffer et al. 1999, Basri and Martín 1999) and IC 2391 (Barrado y Navascués, Stauffer and Patten 1999). In both cases the ages resulting from the location of the LDB, 65-90 Myr and 53±5 Myr for α Persei and IC 2391, respectively, are several tens of Myr older than those determined from the turnoff. However, convective overshooting in massive stars may affect this age determination. The systematically older "lithium ages" could be an indication that indeed overshooting takes place in stars of the upper main sequence.

Brown dwarfs have also been discovered in very young star forming regions (Luhman et al. 1997, Newh́auser and Comerón 1998, Béjar, Zapatero-Osorio and Rebolo 1999). At very young ages, the lithium test cannot help as a substellar discriminator because there is no sufficient time for lithium to be depleted in very low-mass stars. However, the presence of lithium can give confidence on any brown dwarf candidate in star forming regions. An example of an extremely

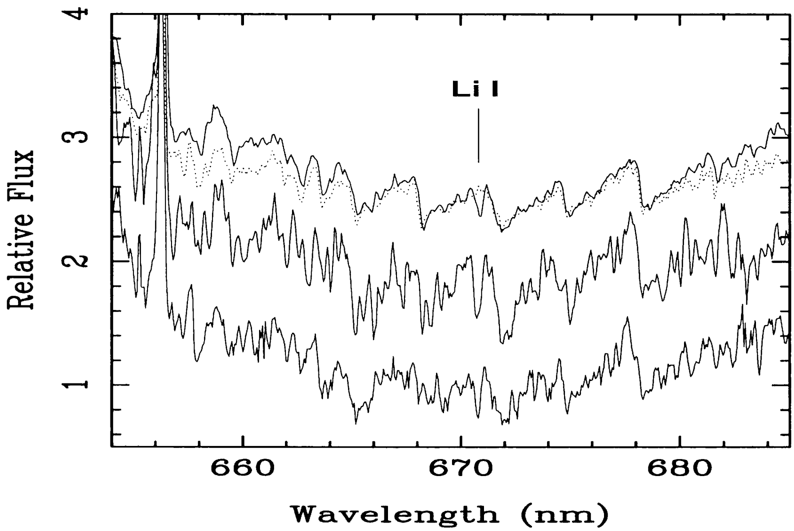

Figure 3. The lithium resonance doublet in spectra of several young brown dwarfs. From top to bottom: σOri 27, Calar 3 and Teide 1. The spectrum of the star vB 10, with no lithium has been overplotted (dotted line).

young brown dwarf discovered by Béjar et al. (1999) in the σ Orionis cluster (age 1-5 Myr) is displayed in Figure 3 where it is plotted next to older and more massive Pleiades brown dwarfs with similar spectral type. Hα can be seen in emission in the three objects.

3.2. Brown dwarf companions

Imaging techniques have revealed three brown dwarfs bounded to nearby stars. The first was Gl 229 B (Nakajima et al. 1995) a cool "methane" brown dwarf in orbit around a M1 V star at 5.7 pc from the Sun. Its effective temperature ($\sim$ 950 K) is so low that most Li atoms are forming part of molecules and consequently it is expected a very weak Li I resonance doublet. The second detected brown dwarf companion was G 196-3 B (Rebolo et al. 1998), it is in orbit around a very young, extremely active M3 dwarf star at a distance in the range 15 to 27 pc from the Sun. The brown dwarf which can be seen in Fig. 4 has an estimated mass of 25±10 Myr, and the spectral energy distribution of an early L-type dwarf according to the recent classification scheme proposed by Kirkpatrick et al. (1999) and Martín et al. (1999). In Fig. 4 it is also plotted the low resolution optical spectrum and the detection of lithium which guarantees that we are dealing with a bona fide brown dwarf. The estimated effective temperature of this object is $\sim$ 1800 K. More recently, Burgasser et al. (2000) have found the third companion brown dwarf, a cool "methane" dwarf in orbit around an M-type star.

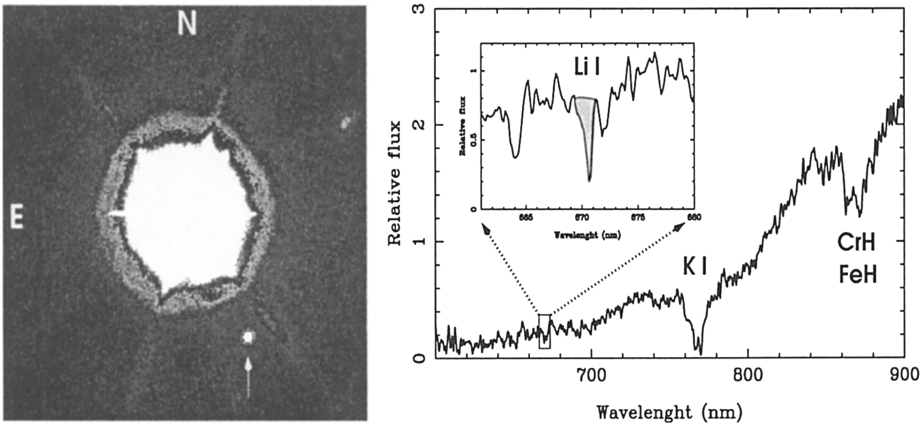

Figure 4. The brown dwarf companion G 196-3 B, identification image in the I band, low resolution optical spectroscopy and intermediate dispersion spectrum showing the presence of lithium (after Rebolo et al. 1998.

3.3. Free-floating brown dwarfs in the solar neighborhood

Nearby free-floating brown dwarfs have been discovered as a result of proper motion surveys (Kelu 1, Ruiz et al. 1997), large scale IR surveys like the DEep Near-Infrared Sky (DENIS, Delfosse et al. 1997) and 2-Micron All-Sky Survey (2MASS, Kirkpatrick et al. 1999), and more recently by the SLOAN Digital Sky survey (Strauss et al. 1999). As expected from the findings in stellar clusters, brown dwarfs are populating the solar neighborhood in significant numbers. Examination of the first 371 sq. deg of 2MASS data have produced 20 objects later than M9.5 V which can be classified as L dwarfs (Kirkpatrick et al. 1999). These objects can be either stellar or substellar and span the effective temperature range between 2000 and 1200 K. In their spectra, the characteristic metallic oxides of M dwarfs are replaced by metallic hydrides and neutral alkali metals as the most remarkable spectroscopic features. About one third of the L dwarfs show strong lithium lines in their spectra (typical equivalent widths are several Å, with a strongest reported detection of 15 Å). Most of these brown dwarfs with lithium will have masses below 0.065 $M_\odot$. The remaining L dwarfs where lithium has not been detected can either be more massive brown dwarfs or simply very low mass stars. Unfortunately, their distances are not sufficiently well known to determine accurate luminosities and subsequently constrain their masses using evolutionary models. It is quite likely that the early L dwarfs are indeed very low mass stars just above the hydrogen burning mass limit. Spectra of L dwarfs showing lithium absorption are plotted in Fig. 5.

Cooler free floating "methane" brown dwarfs whose spectra resemble that of Gl 229 B, have been discovered in the last two years (Strauss et al. 1999, Burgasser et al. 1999, Leggett et al. 2000). These intrinsically fainter objects have effective temperatures close or below 1000 K which do not favor the detection of lithium. Some of these objects could be old massive brown dwarfs ($m \geq 0.065\ M_\odot$) which have cooled significantly and have not retained any lithium

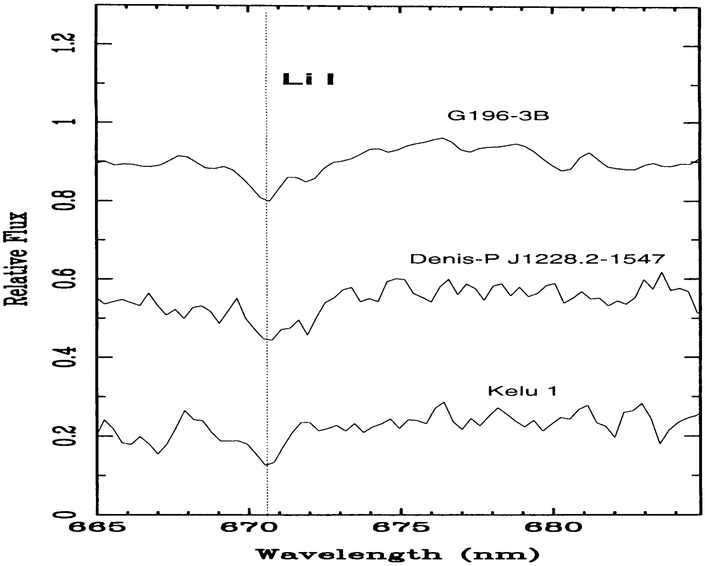

Figure 5. Spectra of several L dwarfs in the region of the lithium resonance doublet.

because burning took place in their interiors. Some other could be younger less massive brown dwarfs where lithium will be preserved for ever.

4. The formation of Li lines in brown dwarfs.

The computations by Rebolo et al. (1992), Magazzù et al. (1993), and Pavlenko et al. (1995) clearly revealed the formation of strong Li I λ670.8 nm lines in the spectra of cool dwarfs with temperatures above 1800 K showing that Li is detectable in the forest of molecular bands expected at these temperatures. Pavlenko et al. (1995) analyzed in detail the LTE and NLTE formation of Li I lines using Allard (1990) model atmospheres of $T_{\rm eff}$ 2000, 2500 and 3000 K. In these computations, the dissociation equilibria for seven Li molecules (LiH, LiO, LiCl, LiF, LiBr, LiI, LiOH) was taken into account. More than 20 atoms in two ionization states and 54 molecules were included in the state equation system. The synthetic spectra were able to reproduce the TiO bands in the region around the Li resonance line, correctly describing positions and intensities of the observed bands. The resulting LTE computations showed the formation of prominent Li I 670.8 nm lines with equivalent widths of several Å. The NLTE effects were found to be small, less than 0.1 dex in abundance. LTE and NLTE curves of growth for the weaker Li I lines at 610.3 and 812.6 nm. were also given. Very recently, Pavlenko, Zapatero-Osorio and Rebolo (2000) have produced synthetic spectra using cooler model atmospheres (effective temperatures in the range 2000-1000 K) suitable to describe the new L dwarfs. The synthesis code was based on that of Pavlenko et al. (1995) but extended the number of considered molecular species up to 100 and included detailed opacities for the most relevant bands. The new computations show that the alkali elements Li, Na, K, Rb and Cs govern the optical spectra of the cooler L dwarfs and that there is a need for implementation of additional opacity in the computations in order to reproduce the far red spectral energy distribution. This additional opacity could be associated to absorption or scattering processes in the atmospheres of cool dwarfs and its dependence with frequency can be simply described by a power law of the form $a_\nu = a_0(\nu/\nu_0)^N$ where the parameters N and a_0 are determined from the observations and ν_0 is arbitrarily adopted as the frequency of the KI resonance line at 769.9 nm. It was found that $N = 4$, corresponding to the case of pure Rayleigh scattering, is adequated for all the objects examined so far. The effects of additional dust opacity on the formation of Li I lines (resonance and subordinate ones) also deserve detailed consideration. The computations show that both, the resonance line at 670.8 nm, and the subordinate lines at 601.3 nm and 812.6 nm are very sensitive to the additional opacity.

Table 1. Equivalent widths (Å) of the Li I resonance doublet at λ670.8 nm computed for cosmic Li abundance ($\log N(\mathrm{Li}) = 3.2$) and gravity $\log g = 5.0$ (after Pavlenko et al. 2000).

T_{eff}	a_o		
	0.00	0.01	0.10
1000 K	17	8	0.6
1200 K	30	12	0.7
1400 K	42	21	0.9

The predicted equivalent widths for the 812.6 nm line, assuming fully preserved lithium, are rather small, ranging from EW= 0.4 Å to 0.04 Å for effective temperatures in the range 2000 K to 1200 K. These EWs are significantly reduced by the inclusion of the additional opacity described above. In Table 1, equivalent widths of the Li resonance doublet at 670.8 nm are listed for several of the coolest model atmospheres (1400-1200 K) considered in Pavlenko et al. (2000). In the absence of any additional opacity, we would expect rather strong Li resonance lines in the spectra of objects as cool as Gl 229 B. The chemical equilibrium of Li species, still allow a sufficient number of Li atoms produce a rather strong resonance feature. However, it is expected a very dusty atmosphere in Gl 229 B, and for the best value of the opacity parameter a_0 derived for this object (a_0=0.1) there is little hope to detect any signature from atomic lithium in its spectrum. It is interesting to note, that in much less dusty atmospheres of similar effective temperature it could be possible to achieve the detection of lithium.

Another important issue is the variability of the lithium lines due to changes in the physical conditions of these atmospheres. In particular, changes in the dust content (condensation) can modify the atmospheric opacity and lead to detectable variations in the EWs of the lithium lines. As a consequence, weak lithium lines do not necessarily imply a depletion of this element. The observed LiI variability in Kelu 1 (with changes in EW by factor 5), could be an indication

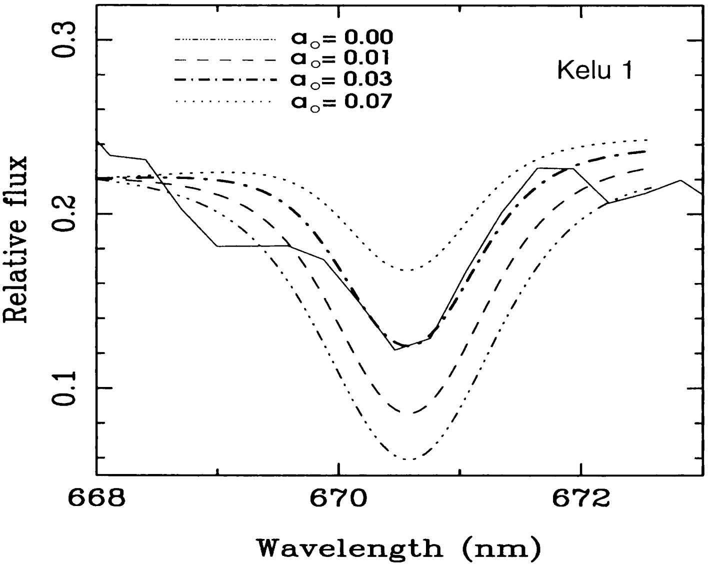

Figure 6. Spectrum of the brown dwarf Kelu 1 (T_{eff}=2000 K, log g=5.0) in the Li region (solid line) and computed spectra assuming a cosmic Li abundance but various atmospheric opacities.

of metheorological changes in the atmosphere of this rapidly rotating cool object. In Fig. 6 several spectral synthesis show the sensitivity of the lithium line to the extra opacity in the atmosphere. The additional opacity parameters which give the best fit for the observed lithium line in Kelu 1 (EW =6.5±1.0 Å) coincide with those also providing the best fit to the whole optical spectrum. The obtained lithium abundance is consistent with complete preservation.

5. Concluding remarks

Observations in very late type M dwarfs and L dwarfs have confirmed early claims that the resonance lithium doublet would be observable in very cool dwarfs. The lithium test is now widely used as a mean to confirm the substellar nature of brown dwarfs. Detection of lithium is rutinary achieved in brown dwarf candidates in stellar clusters and in the solar neighborhood and most bona fide brown dwarfs known at present have been recognized through the presence of lithium in their spectra. Another promising area of activity promoted by these lithium searches is the new method for datation of clusters based on the empirical determination of the end of the lithium depletion at the bottom of the main sequence.

While large progress has been achieved in understanding the formation of lithium lines in cool atmospheres, there are many aspects that require refinement to fully exploit the potential of this element. In particular, it is important to investigate the formation of lines from molecular species containing lithium, to refine the spectral synthesis computations and generate better model atmospheres. Future searches may provide detection of the more fragile ^{6}Li isotope in brown dwarfs. Detection of metal-poor halo brown dwarfs at suitable distances from the Sun will allow investigation of their lithium content which could open new ways to examine the early galactic evolution of this element.

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