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LETTER TO THE EDITOR

Lithium in the Hyades L5 brown dwarf 2MASS J04183483+2131275★,★★

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ABSTRACT

Aims. From the luminosity, effective temperature and age of the Hyades brown dwarf 2MASS J04183483+2131275 (2M0418), substellar evolutionary models predict a mass in the range 39−55 Jupiter masses ($M_{\rm Jup}$) which is insufficient to produce any substantial lithium burning except for the very upper range >53 $M_{\rm Jup}$. Our goal is to measure the abundance of lithium in this object, test the consistency between models and observations and refine constraints on the mass and age of the object.

Methods. We used the 10.4-m Gran Telescopio Canarias (GTC) with its low-dispersion optical spectrograph to obtain ten spectra of 2277 s each covering the range 6300–10 300 Å with a resolving power of $R \sim 500$.

Results. In the individual spectra, which span several months, we detect persistent unresolved Hα in emission with pseudo equivalent widths (pEW) in the range 45–150 Å and absorption lines of various alkalis with the typical strengths found in objects of L5 spectral type. The lithium resonance line at 6707.8 Å is detected with pEW of 18 ± 4 Å in 2M0418 (L5).

Conclusions. We determine a lithium abundance of log N(Li) = 3.0 ± 0.4 dex consistent with a minimum preservation of 90% of this element which confirms 2M0418 as a brown dwarf with a maximum mass of 52 $M_{\rm Jup}$. We infer a maximum age for the Hyades of 775 Myr from a comparison with the BHAC15 models. Combining recent results from the literature with our study, we constrain the mass of 2M0418 to 45–52 $M_{\rm Jup}$ and the age of the cluster to 580–775 Myr (1σ) based on the lithium depletion boundary method.

Key words. stars: low-mass – brown dwarfs – open clusters and associations: individual: Hyades – techniques: photometric – techniques: spectroscopic – surveys

1. Introduction

Among the light elements, ^{7}Li plays a special role as a discriminant of substellar nature. In stellar interiors the ^{7}Li nuclei are burnt via collisions with protons at temperatures above 2.5×10^6 K, but solar metallicity brown dwarfs (BDs) with masses below 50 $M_{\rm Jup}$ cannot reach this temperature (e.g. Baraffe et al. 2003; Magazzu et al. 1993). Lithium is preserved from destruction in these BDs and should be present in their atmospheres with an abundance close to the cosmic value (Rebolo et al. 1992). Strong lithium features have been seen in a large variety of BDs (Faherty et al. 2014; Kirkpatrick et al. 2008; Lodieu et al. 2015; Rebolo et al. 1996, 1998).

Objects more massive than 50 $M_{\rm Jup}$ progressively burn lithium as they age. In such objects the lithium abundance is a very sensitive function of mass and age, parameters rather difficult to determine for most isolated BDs. While the detection and abundance determination of lithium provides an important indication of substellarity, it has by itself a limited capacity to restrict these two parameters in such objects (Baraffe et al. 1998, 2015; Feiden et al. 2015; Siess et al. 2000).

However, the coevality of the members of a stellar cluster offer a remarkable opportunity to test the predictions of lithium destruction as a function of mass for BDs. The Li-mass (Li-effective temperature or Li-luminosity) depletion curves are very sensitive to the age of a cluster and systematic observations of lithium in the substellar domain of a cluster can constrain its age (Barrado y Navascués et al. 2004; Dobbie et al. 2010; Jeffries et al. 2003; Manzi et al. 2008; Oliveira et al. 2003; Stauffer et al. 1998). In addition, an empirical determination of the Li-mass relation provides physical insight on the parameters which govern the maximum temperature reached in the interior of BDs, and in particular on the equation of state.

The luminosity and effective temperature ($T_{\rm eff}$) of the L5 member of the Hyades 2MASS J04183483+2131275 (hereafter 2M0418; Pérez-Garrido et al. 2017), indicates a mass range of 39–55 $M_{\rm Jup}$ comparing its $J-K$, $J-W2$, and $W1-W2$ colours with the AMES-Dusty evolutionary models (Allard et al. 2001; Chabrier et al. 2000), hence a significant preservation of the original lithium content is expected. However, the conversion from BD parameters (luminosity and $T_{\rm eff}$) to masses are subject

★ Based on observations made with the Gran Telescopio de Canarias (GTC) installed in the Spanish Observatorio del Roque de los Muchachos of the Instituto de Astrofísica de Canarias, in the island of La Palma (programme GTC77-16B).

★★ The spectrum (FITS file) is only available at the CDS via anonymous ftp to cdsarc.u-strasbg.fr (130.79.128.5) or via http://cdsarc.u-strasbg.fr/viz-bin/qcat?J/A+A/615/L12

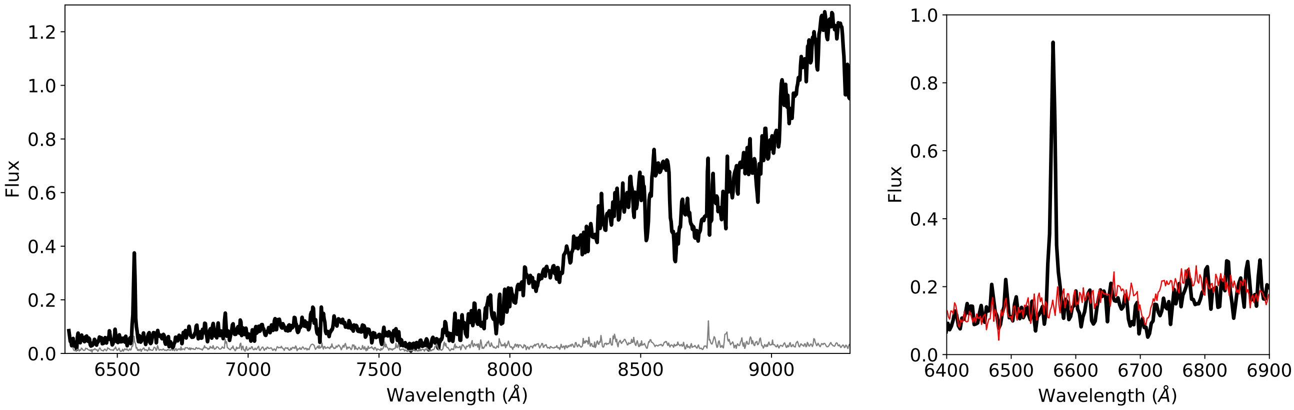

Fig. 1. Full GTC/OSIRIS spectrum of the Hyades L5 dwarf 2M0418 (black) calibrated in flux with the standard deviation from the ten individual optical spectra (gray). The *right-hand* plot shows a zoom on Hα in emission and lithium in absorption. Overplotted in red is the optical spectrum of the field L5V dwarf 2MASS J12392727+5515371 which exhibit lithium in absorption (Kirkpatrick et al. 1999).

to various uncertainties: if the mass were only 10% higher, i.e. 60 $M_{\rm Jup}$, a significant lithium destruction (90%) could have taken place by the age of the Hyades. This object offers an opportunity to observe a relatively old BD (>500 Myr) with fully preserved lithium, or alternatively, if depletion is already undergoing, to impose very narrow constraints on its mass from theoretical lithium depletion evolutionary curves. In the case of full preservation the lithium resonance line is expected to be rather strong in L dwarfs (Kirkpatrick et al. 2008; Pavlenko et al. 2000) and detectable in such faint object ($R \sim 23$ mag). Lithium has been detected even in cooler objects like the very nearby binary BD Luhman 16AB (Faherty et al. 2014; Lodieu et al. 2015) showing that the formation of Li-based molecules (e.g. LiH, LiCl; Lodders 1999) is not a problem for detecting the Li resonance doublet at these temperatures.

In this manuscript, we present spectroscopic observations of 2M0418 (Sect. 2) and derive its physical parameters (Sect. 3). We discuss the strong lithium feature at 6707.8 Å, which according to spectral synthesis models is consistent with a cosmic abundance of lithium and therefore, with full (or close to full) preservation in this BD. We also present the detection of Hα in emission Sect. 5. Finally, we derive the age of the Hyades combining our detection of lithium and the presence of lithium in higher mass BDs (Sect. 6). For older clusters, the lithium depletion boundary moves to later-type and fainter members, which explains the age of the cluster has only been recently addressed by Martín et al. (2018) and this work.

2. Spectroscopic observations

We collected ten optical spectra with OSIRIS (Optical System for Imaging and low-intermediate Resolution Integrated Spectroscopy; Cepa et al. 2000) on the 10.4-m GTC at Observatorio del Roque de los Muchachos (La Palma, Spain) over several nights between 23 January and 28 February 2017 as part of programme GTC77-16B (PI Pérez-Garrido).

OSIRIS is equipped with two 2048 × 4096 Marconi CCD42-82 detectors offering a field of view of approximately 7 × 7 arcmin^2 with a binned pixel scale of 0.25 arcsec. We employed the R1000R grating with a slit of 1.23 arcsec, yielding a spectral resolution of approximately 500 over the 6300–10 300 Å range.

We obtained five separate observing blocks on five distinct nights: 23 January, 2, 16, 26, and 28 February 2017. Each block was made of two individual spectra of 2277 s nodded along the slit to improve the sky subtraction, yielding a total exposure of 6.325 h. Observations were obtained under seeing in the 0.7–1.2 arcsec range, clear conditions and gray or dark time.

Table 1. Spectral indices for the intermediate-age mid-L dwarf 2M0418.

SpT	TiO-a	TiO5	CrH-a	Rb-a	Na-a	Na-b	FeH-a
L5	1.116	1.210	1.726	1.489	1.009	1.024	1.214

We reduced the optical spectra under the IRAF environment (Tody 1986, 1993) in a standard manner. First, we median-combined the bias and flat-fields taken during the afternoon. We subtracted the mean bias from the raw spectrum of the target and divided by the normalised flat field. We subtracted the first position from the second one of each observing block and extracted optimally the individual spectra by choosing manually aperture and sky regions[1] We calibrated each spectrum in wavelength with the arc Xe+Ne+HgAr lamps observed during the preceding afternoon. We combined all ten spectra with a median filter and estimate the error at each wavelength from the standard deviation of the individual spectra (Fig. 1).

We computed various spectral indices defined by Kirkpatrick et al. (1999) and Cruz et al. (2009) for this intermediate-age mid-L dwarf. We report the values in Table 1. We observe that these values are in agreement with intermediate-age L dwarfs comparing with the ranges reported by Cruz et al. (2009), consistent with the age of the Hyades cluster. The cesium line at 8521 Å appears also weaker than in field L5 dwarfs, supporting the intermediate-age of the cluster because this line is gravity-sensitive. The other spectral indices available in the literature are affected by low signal-to-noise regions of our combined spectrum so we do not report them in this work.

3. Effective temperature and luminosity

We computed the distance of 2M0418 using the latest version of the BANYAN Σ algorithm (Gagné et al. 2018) which provides a kinematic distance estimated based on the *XYZ* and

[1] We used the routine `apsum` in IRAF (Tody 1986, 1993).

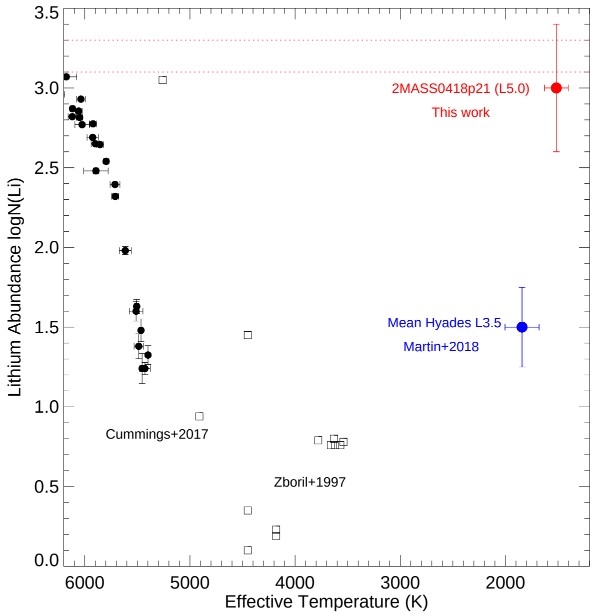

Fig. 2. Lithium abundances (in the scale of log N(H) = 12) versus $T_{\rm eff}$ for Hyades solar-type stars (black dots; Cummings et al. 2017), K5–M4 stars (upper limits; Zboril et al. 1997), the mean value for L3.5 members (blue dot; Martín et al. 2018), and the BD 2M0418 (red dot). The range of initial lithium meteoritic content is shown with red dotted lines as an upper limit of the possible content in BD atmospheres.

UVW distribution of Hyades members. yielding a mean value of 40.6 ± 2.7 pc[2].

We estimated the $T_{\rm eff}$ of 2M0418 using the most recent polynomials based on the spectral types and absolute H-band magnitudes of field M6–T9 (Filippazzo et al. 2015). We derived consistent mean $T_{\rm eff}$ of 1581 ± 113 and 1516 ± 29 K based on the L5 spectral type and the UKIDSS H-band magnitude (Lawrence et al. 2007) corrected for the distance (40.6 ± 2.7 pc). The uncertainties on the $T_{\rm eff}$ does include the dispersion from the polynomials of Filippazzo et al. (2015) but not the uncertainty on the spectral type determination. To summarise, we assign a mean $T_{\rm eff}$ of 1581 ± 113K to 2M0418. We note that we might be over-estimated the $T_{\rm eff}$ of this L5 member of the Hyades by up to about 50 K because it has an age lower than the field dwarfs in the sample of Filippazzo et al. (2015). The young sample in that study indicates a temperature 100 K lower for L dwarfs with ages between 10 and 120 Myr. We plot this measurement in Fig. 2 where we display the evolution of the Li pEW in Hyades solar-type stars (Cummings et al. 2017; Thorburn et al. 1993), the upper limits on the lithium features in the optical spectra of K and M low-mass stars (Stauffer et al. 1997a) with $T_{\rm eff}$ taken from Rajpurohit et al. (2013), and the mean value for Hyades L3.5 dwarfs (Martín et al. 2018).

In Table 2 of Pérez-Garrido et al. (2017), we derived a bolometric luminosity of 2.80×10^{29} erg s^{-1}, translating in $\log(L_{\rm bol}/L_{\odot})$ of -4.14 dex. We re-calculated the value of $\log(L_{\rm bol}/L_{\odot})$ using the UKIDSS K-band magnitude (15.230 ± 0.022), the distance from BANYAN, and the K-band bolometric correction for a L5 dwarf (3.30 ± 0.05 mag) from Filippazzo et al. (2015), yielding a slightly lower value of -4.30 ± 0.07 dex (Table 2).

Table 2. Physical parameters of 2M0418 derived in this study.

SpT	L5.0 ± 0.5
$\log(L_{\rm bol}/L_{\odot})$	-4.30 ± 0.07 dex
$T_{\rm eff}$	1581 ± 113 K
pEW (Li)	18 ± 4 Å
pEW (Hα)	-150 to -45 Å
Li abundance	-3.0 ± 0.4 dex

4. New lithium detection in 2M0418

The lithium test was proposed in the 1990s to distinguish between low-mass stars and BDs (Rebolo et al. 1992). The technique relies on the detection of lithium in absorption at 6707.8 Å for late-M and L dwarfs straddling the stellar-substellar boundary. If the lithium is detected in an ultracool dwarf, the object is substellar. If not, it is a high-mass BD or a very low-mass star.

Figure 1 shows the combined optical spectrum of 2M0418, calibrated in flux. In the right-hand side panel we show the region of the optical spectrum around the Li absorption including a significant part of the continuum to appreciate the detection. We measure a pseudo-equivalent width (pEW) of 18 ± 4 Å (1σ), consistent with the compilation of field L5 dwarfs exhibiting lithium in absorption We derived the error bars from the dispersion of the 10 individual spectra of the target in two continuum regions around the lithium line applying the equation 7 of Cayrel (1988; Cruz et al. 2009; Kirkpatrick et al. 1999, 2000, 2008; Lodieu et al. 2015; Pavlenko et al. 2007; Zapatero Osorio et al. 2014). In Fig. 1 we overplot in red the spectrum of a field L5V, 2MASS J12392727+5515371, exhibiting one of the strongest lithium absorption among mid-L dwarfs and a decent signal-to-noise ratio in the region of lithium. We infer a pEW of 15 ± 2 Å and a full-width-half-maximum of 26 ± 4 Å, in agreement with the 14 Å reported by Kirkpatrick et al. (1999).

The mass of 2M0418 was estimated by Pérez-Garrido et al. (2017) using the near/mid-IR colours reported in Table 1 of that paper and the evolutionary models of the Lyon group (Allard et al. 2001; Chabrier et al. 2000). A likely mass between 39–55 $M_{\rm Jup}$ with central value of 48 $M_{\rm Jup}$ was inferred. Our new detection of lithium confirms the substellarity of 2M0418 with an upper limit of ~60 $M_{\rm Jup}$ (see Sect. 6).

Figure 2 shows the evolution of the lithium pEWs as a function of $T_{\rm eff}$ with a minimum around K and M dwarfs due to the burning of lithium. Cummings et al. (2017) gives direct A(Li) = log (N(Li)/N(H)) measurements for solar-type members of the Hyades. We measured upper limits of about 0.1 Å on the pEWs of the lithium in the optical spectra published in Stauffer et al. (1997b) and kindly provided by the author. These values translate into lithium abundances below log N(Li) = 1.0 based on the work by Zboril et al. (1997) which quote equivalent widths of a few Å for field K5–M6 dwarfs equivalent to abundances around the plateau at 0.85. We added 2M0418 in Fig. 2 for which we inferred the abundance as follows. We looked at the curve of growth created from the BT-Settl atmospheric structure computed by Allard et al. (2012) and the theoretical code WITA2 of Pavlenko (1997) and Pavlenko et al. (2007) for gravities of $\log(g) = 4.5$ and 5.0 dex and $T_{\rm eff}$ of 1600 K, 1800 K, 2000 K, 2100 K, and 2200 K (green dots in Fig. 2).

[2] http://www.exoplanetes.umontreal.ca/banyan/banyansigma.php?radeg=64.645125&pmra=124&pmdec=-53&hrv=38&!plx=&submit=Submit&dec=21.524306&epmra=7&epmdec=6&ehrv=2.9&eplx=&targetname=0418

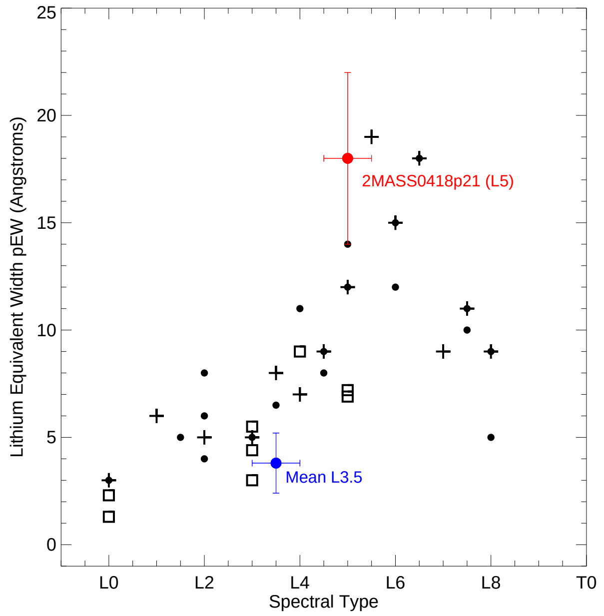

Fig. 3. Lithium pseudo-equivalent widths (pEWs) of L and T dwarfs. Measured lithium pEW for field (dots and crosses; Kirkpatrick et al. 2000, 2008) and young L dwarfs (open squares; Cruz et al. 2009). 2M0418 is highlighted with a red dot and the mean value for L3.5 members of the Hyades in blue.

The closest predicted pEW of lithium at 6707.8 Å is given by $\log(g) = 5.0$ dex and $T_{\mathrm{eff}} = 1600$ K (17.9 Å), yielding an abundance of log N(Li) = 3.0 ± 0.4 dex. The uncertainty of 0.4 dex on the abundance comes mainly from the error on the pEW. We also added to the plot the mean abundance derived from the mean pEW of lithium derived for two Hyades L3.5 members (Martín et al. 2018).

5. Hα emission

Since the first optical spectrum collected on 25 January 2015 with GTC/OSIRIS (Pérez-Garrido et al. 2017), we see persistent but variable emission in Hα at 6562.8 Å. We measured the pEW on each of the ten individual spectra and found a variation in the strength of the Hα line from −150 Å to −45 Å over the period of approximately one month (23 January till 28 February 2017).

6. Age of the Hyades cluster

In this section we discuss the constraints that we can set on the age of the Hyades cluster based on the presence of lithium in absorption in the optical spectrum of 2M0418.

The study of chondritic meteorites suggests an original lithium elemental abundance A(Li) = 3.28 ± 0.05 (Lodders 2003) in the solar system. We assume a similar elemental abundance in the Hyades cluster. In Fig. 2 we observe that the maximum abundance of solar-type members of the Hyades lies around 3.0 dex, very similar to the lithium abundance of the interstellar medium (Ferlet & Dennefeld 1984; Lemoine et al. 1993) and the Pleiades (Boesgaard et al. 1988; Garcia Lopez et al. 1994). Based on the upper envelope of L dwarfs with clear lithium absorption lines, 2M0418 might have fully preserved its lithium because the largest pEW in field L dwarfs is 15 Å (filled dots in Fig. 3) for 2MASSW J1239272+551537 (Jameson et al. 2008; Kirkpatrick et al. 2000) resolved into a 0.21″ binary (Gizis et al. 2003). Our lithium abundance computations were implemented for 1D model atmospheres under the assumption of local thermodynamic and hydro-static equilibrium with no sinks of energy. The chemical equilibrium was computed for ≈100 molecular species with WITA2 (Pavlenko 1997, 2013; Pavlenko et al. 2007).

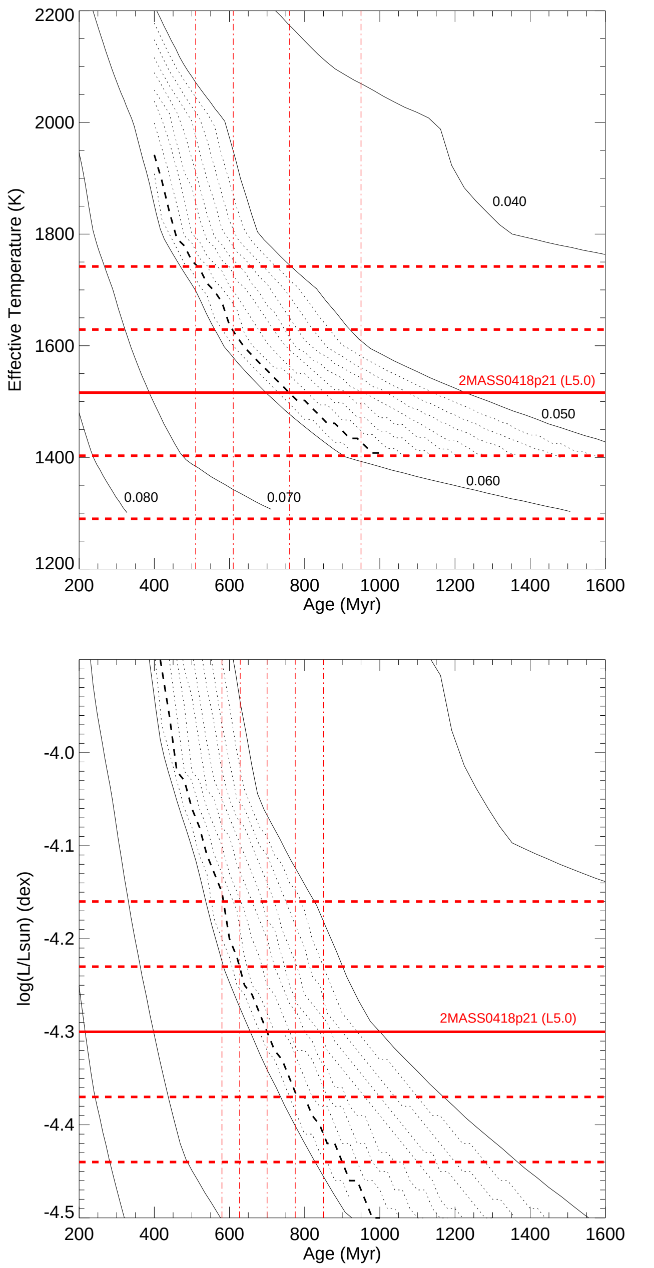

Fig. 4. *Top*: T_{eff} vs. age of isomasses from the BHCA95 models for masses of 10–80 M_{Jup} by steps of 1 M_{Jup} (black lines). The 51–59 M_{Jup} isomasses are highlighted with black dotted lines for a limited age range (400–1400 Myr). *Bottom*: Luminosity vs. age. 2M0418 is marked with a red line and the 1 and 2σ error bars shown as dashed lines.

The detection of lithium in 2M0418 sets a upper limit on its mass and on the age of the Hyades. We looked at the preservation of lithium predicted by the latest BHAC15 models (Baraffe et al. 2015) for masses below 60 M_{Jup} (black lines in Fig. 4). Due to the limited steps in masses, we requested to I. Baraffe the prediction of lithium for ages between 400 and 1.4 Gyr and masses in the 50–60 M_{Jup} range. The BHAC15 models predict ratios of lithium to meteoritic lithium of ~93–95%, 89–91%, and 81–85% for masses of 50, 51, and 52 $M_{\rm Jup}$, respectively (black dotted lines in Fig. 4). The evolution of this ratio is very quick, implying that the upper mass of 2M0418 is constrained to 52 $M_{\rm Jup}$ assuming levels of depletion smaller than 20%. However, we caution that this upper limit depends on models and should be validated in the future with dynamical masses of mid-L dwarf binary members of the Hyades. Therefore, the 1σ upper limit on the age of the Hyades is set to 775 and 950 Myr from the luminosity and $T_{\rm eff}$ of 2M0418, respectively (Fig. 4).

Using a similar study of four L3–L4 photometric, astrometric, and radial velocity members of the Hyades, Martín et al. (2018) infer a lower limit of 580 Myr on the age of the cluster, which combined with our upper limit would correspond to a range of 580–775 Myr (mean of 700 Myr) and 580–950 Myr (mean of 760 Myr) at 1σ for the Hyades from the luminosity and $T_{\rm eff}$ of 2M0418. This age range is in agreement with the original estimate of 625 ± 50 Myr from Maeder & Mermilliod (1981) and the recent lithium depletion age of Martín et al. (2018) but on the lower end of the 750 ± 100 Myr determination (Brandt & Huang 2015a,b). We remark the importance of identifying a large sample of L dwarfs to refine the age of the cluster and impose further constraints on the physics of the interior of BDs. The Hyades is the oldest open cluster with an age derived by the lithium depletion boundary technique.

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