Search for the sub-stellar lithium depletion boundary in the open star cluster Coma Berenices

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ABSTRACT

Aims. We mainly aim to search for the lithium depletion boundary (LDB) among the sub-stellar population of the open star cluster Coma Berenices.

Methods. Since the number of brown dwarf candidates in Coma Ber available in the literature is scarce, we carried out a search for additional candidates photometrically using colour–magnitude diagrams combining optical and infrared photometry from the latest public releases of the following large-scale surveys: the United Kingdom InfraRed Telescope Infrared Deep Sky Survey (UKIRT/UKIDSS), the Panoramic Survey Telescope and Rapid Response System (Pan-STARRS), the Sloan Digital Sky Survey (SDSS), and AllWISE. We checked astrometric consistency with cluster membership using Gaia DR2. A search for Li in three new and five previously known brown dwarf candidate cluster members was performed via spectroscopic observations using the OSIRIS instrument at the 10.4 m Gran Telescopio de Canarias (GTC).

Results. A couple dozen new photometric candidate brown dwarfs located inside the tidal radius of Coma Ber are reported, but none of these are significantly fainter and cooler than previously known members. No LiI resonance doublet at 6707.8 Å was detected in any of eight Coma Ber targets in the magnitude range J = 15–19 and G = 20–23 observed with the GTC. Spectral types and radial velocities were derived from the GTC spectra. These values confirm the cluster membership of four L2–L2.5 dwarfs, two of which are new in the literature.

Conclusions. The large Li depletion factors found among the four bona fide sub-stellar members in Coma Ber implies that the LDB must be located at spectral type later than L2.5 in this cluster. Using the latest evolutionary models for brown dwarfs, a lower limit of 550 Myr on the cluster age is set. This constraint has been combined with other dating methods to obtain an updated age estimate of 780 ± 230 Myr for the Coma Ber open cluster. Identification of significantly cooler sub-stellar cluster members in Coma Ber awaits the advent of the Euclid wide survey, which should reach a depth of about J = 23; this superb sensitivity will make it possible to determine the precise location of the sub-stellar LDB in this cluster and to carry out a complete census of its sub-stellar population.

Key words. brown dwarfs – open clusters and associations: individual: Coma Berenices – techniques: spectroscopic – open clusters and associations: general – stars: abundances

1. Introduction

Characterisation of brown dwarfs (BD) in open clusters is useful to test models of sub-stellar evolution and to provide benchmarks to constrain ages and masses of BD candidates in the solar neighbourhood. Particular interest has been devoted to the study of the most stable isotope of lithium (Li7), which is destroyed in stellar interiors at temperatures above 2.5 × 106 K, that is before settling on the main sequence, but not in BDs with masses below about 0.06 M⊙ (Pozio 1991; Magazzu et al. 1991; Rebolato et al. 1992). Hence detection of the Li I resonance doublet can be used to break degeneracies in the Hertzsprung Russell diagram between stellar and sub-stellar mass objects (Magazzu et al. 1993; Martín et al. 1994a). In a coeval population, such as those of open clusters, the Li depletion boundary (LDB) provides a reliable dating method that has been used quite extensively in young open clusters and associations, such as the Pleiades (Stauffer et al. 1998) and IC 2602 (Dobbie et al. 2010). Even though the range of applicability of the LDB method was thought to be restricted to ages between 20 Myr and 200 Myr (Burke et al. 2004; Juarez et al. 2014), it has been shown recently that this method can be extended to older clusters such as the Hyades, for which an LDB age of 650 ± 70 Myr has been obtained (Lodieu et al. 2018a; Martín et al. 2018). The upper age limit to the application of the LDB in open clusters may take place at ages older than 1 Gyr when the Li brown dwarfs become so cold that atomic Li is no longer present in their atmospheres because it is locked in molecules such as LiH. So far, the coolest brown dwarfs for which a Li detection has been reported (Faherty et al. 2014; Lodieu et al. 2015) is the T0 secondary of the nearest BD binary (Luhman 2013).

Coma Berenices (hereafter abridged to Coma Ber; an alternative name is Melotte 111) is the second nearest open cluster to the Sun (86 pc; van Leeuwen 2009; Tang et al. 2018). Updated information about the cluster properties, including the
identification of a leading and a trailing tail extending 50 pc away from the cluster centre, can be found in Tang et al. (2019). Coma Ber has a well-defined core with a tidal radius of 6.9 pc, an elongated shape, tidal trails, is on its way to mixing with a nearby younger moving group, and is located 60 pc away from the cluster centre (Fürnkranz et al. 2019; Tang et al. 2019). Coma Ber has solar metallicity and negligible reddening in the line of sight (Taylor 2006). The age has not been well determined, a wide range of ages are found in the literature (300–1000 Myr; Tsvetkov 1989).

Despite ongoing disruption, mass segregation, and the likely large loss of former members, Coma Ber still has about a hundred of low-mass stars (Kraus & Hillenbrand 2007), and it appears to have retained even some BDs still bound to the cluster. Candidate BD members in Coma Ber were identified by Casewell et al. (2006). Follow-up spectra were presented in Casewell et al. (2014) and their masses are estimated to lie between 0.07 and 0.05 $M_\odot$, which straddle the range of masses where the LDB is expected to be reached. Recently, Tang et al. (2018) used the parallaxes from the second data release of Gaia (Gaia Collaboration 2018) to produce a full stellar census of Coma Ber and confirm one of the candidates in Casewell et al. (2014) as a bona fide member. These authors identified two new sub-stellar member candidates for which they assign tentative spectral types of L2 and L4 from low-resolution, near-infrared spectra. These authors estimate a cluster age of 800 Myr from isochrone fitting of massive cluster members; this age is significantly older than has been previously adopted in the literature (400–500 Myr; Kraus & Hillenbrand 2007).

In this paper, we present a photometric search for new faint objects in the core of Coma Ber aimed at increasing the sub-stellar population for lithium depletion boundary (LDB) determination, and a spectroscopic search for Li among the coolest confirmed cluster members. In Sect. 2 we describe a photometric search of very-low-mass (VLM) member candidates of Coma Ber cross-matching optical and near-infrared public surveys. In Sect. 3 we present low-resolution optical spectroscopy of eight VLM and potential BD member candidates collected with the optical spectrograph on the 10.4 m Gran Telescopio de Canarias (GTC). Four of these are confirmed as bona fide sub-stellar cluster members. In Sect. 4 we infer constraints on the age of Coma Ber from the absence of lithium in the four BD members confirmed by us and we provide a revised cluster age combining our results with other dating methods.

2. Search for very-low-mass photometric candidate Coma Ber members

In order to increase the sample of BD targets for LDB determination in Coma Ber, our first step was to look for very red and faint photometric candidates using the UKIR Infrared Deep Sky Survey (UKIDSS; Lawrence et al. 2007) Galactic Clusters Survey (GCS) data release 9 (DR9). The search was limited to point sources fainter than 10 mag to avoid saturation. Detections in the J and K bands with Class parameters between $-2$ (probable point sources) and $-1$ (point sources) were required because L dwarfs have red $J$ and $K$ colours. We launched the query in the UKIRT Wide Field Camera (WFCAM; Casali et al. 2007) Science Archive (Hambly et al. 2008), which returned 234905 sources over an area of 98.8 square degrees. We show the GCS coverage in Coma Ber in Fig. 1, in which we include the tidal radius of the cluster as a large cyan circle (6.9 pc; Tang et al. 2018). The GCS coverage does not reach out to the tidal tails of Coma Ber, which extend up to 50 pc (Tang et al. 2018, 2019; Fürnkranz et al. 2019), but our survey is complete out to a radius of 5.6 deg centred at (RA,Dec) = (186.61,+26.31) degrees.

We cross-matched this input catalogue with the first data release of the Panoramic Survey Telescope and Rapid Response System (Pan-STARRS; Magnier et al. 2013), the Sloan Digital Sky Survey (SDSS; Alam et al. 2015) DR12, and AllWISE (Wright et al. 2010; Cutri et al. 2014) with a matching radius of 3 arcsec. We included the calculation of the proper motions from the baseline between Pan-STARRS and SDSS data, whose mean value lies around 7.2 yr. The similar numbers of sources in the UKIDSS GCS DR9 catalogue and the final catalogue with Pan-STARRS and SDSS show that both optical surveys perfectly complement the infrared photometry of the UKIDSS GCS. We show the GCS coverage in Coma Ber in Fig. 1.

To define conservative photometric selection cuts, we collected known members from the surveys of Casewell et al. (2006, 2014), and Tang et al. (2018) and plotted in various colour-magnitude diagrams depicted in Fig. 2. The most recent survey of Tang et al. (2018) distinguishes candidates with and without parallaxes from the Gaia second data release (DR2) (Gaia Collaboration 2018). We excluded three candidates from Casewell et al. (2006) that lie systematically below the sequence (candidate numbers #6, #11, and #13). The cluster sequence is mainly guided by the two faintest candidates of Tang et al. (2018) with infrared spectra T159 and T191. The sequence of Hyades L dwarfs confirmed, which are spectroscopically (Goldman et al. 2013; Hogan et al. 2008; Bouvier et al. 2008; Martín et al. 2018; Lodieu et al. 2018b) shifted to the distance of ComaBer, also supports the fact that the sequence of Coma Ber is marked by T159 and T191 (Tang et al. 2018), which we used as reference to define our selection lines. Object #12 (=cbd67) of Casewell et al. (2006) is confirmed as a L2.0 member and included in our selection. We note that the 500 Myr isochrone...
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(Allard et al. 2012; Baraffe et al. 2015) and the field sequence of old M, L, and T dwarfs (Dupuy & Liu 2012) tend to lie above the putative sequence of VLM members in Coma Ber. We defined photometric selection criteria in three-colour-magnitudes diagrams, with a set of straight lines going from the brightest to the faintest limits (green dashed lines in Fig. 2) as follows:

- \((J - K, J) \geq 0.73\) from \(J = 11.2\) to 16 mag;
- \((J - K) = (0.75, 16.0)\) from (2.20/20.0);
- \((i_{\text{PS1}} - J, i_{\text{PS1}}) = (1.35, 12.2)\) from (2.50, 18.2);
- \((i_{\text{PS1}} - J, i_{\text{PS1}}) = (2.50, 18.2)\) from (4.00, 22.5);
- \((i_{\text{PS1}} - K, i_{\text{PS1}}) = (2.20, 18.2)\) from (3.55, 18.2);
- \((i_{\text{PS1}} - K, i_{\text{PS1}}) = (3.55, 18.2)\) to (5.00, 22.5).

We started off with the \((J - K, J)\) colour magnitude because it is the most sensitive to red and faint cluster members. Then, we removed those not satisfying the criteria in the \((i - J,i)\) and \((i - K,i)\) diagrams, yielding a list of 2583 candidates labelled as “ComaBer: iK cand” in Fig. 2. We cross-matched this list with the Gaia DR2 catalogue to remove the 2550 sources with Gaia information because the astrometric selection was already done by Tang et al. (2018). We assume that this selection is complete down to the limit of Gaia, corresponding approximately to \(J \geq 16\) mag. Hence, we are left with photometric candidates labelled as “ComaBer: NEW cand not in Gaia” in Fig. 2. We should emphasise that our selection includes cbd10 and cbd67 as photometric candidates (Casewell et al. 2014) as well as T159 and T191 (Tang et al. 2018).

We computed the proper motions from the difference between the PS1 and SDSS positions, taking into account the epoch difference (mean or median around 7.25 yr). The uncertainties on the proper motion is taken has 1.48 times the median absolute deviation (MAD). The MAD is 8.9 and 7.9 mas yr\(^{-1}\), yielding proper motion uncertainties of 13.2 and 11.7 mas yr\(^{-1}\) in RA and Dec, respectively. We analysed the position of these new photometric member candidates in the vector point diagram plotted in Fig. 3. We observe a large dispersion in the proper motions but find some sources with motions consistent with the bulk of parallax and photometric member candidates in Tang et al. (2018), for example \#2963 = T191, \#2816 = T159, \#2938 = ComaBer4. If we apply a 3σ selection based on the uncertainties taken as 1.48×MAD and centred on the mean motion of the cluster (–11.2, –9.2 mas yr\(^{-1}\)), we would keep 8 sources out of the 33 photometric candidates previously selected (\#2963, 2893, 2816, 1412, 1697, 2938, 2940, 2970).

We compile this list of member candidates in Table 1, dividing it up into three sub-samples: (1) 4 sources previously reported by other studies (top panel), 8 photometric candidates with proper motion consistent with the mean motion of the cluster (middle panel), and the remaining 22 photometric candidates (bottom panel).

3. Spectroscopic observations and analysis

3.1. Low-resolution optical spectroscopy

We obtained optical spectra with the Optical System for Imaging and low Resolution Integrated Spectroscopy (OSIRIS: Cepa et al. 2000) instrument on the 10.4 m Gran Telescopio de Canarias (GTC) over two semesters (GTC47-18A and GTC55-19A; PI Martin). All of the data were collected under service mode, except four sources (ComaBer4, 5, 7, and 13), which were observed during a two-night visitor mode campaign on 12 and 13 May 2018 (observer V.J.S. Béjar). The log of the observations is available in Table 2. We requested dark conditions, seeing better than 1.2 arcsec, and spectroscopic conditions for both GTC programmes.

We obtained low-resolution optical spectra with the R1000R grating covering the 5100–10000 Å wavelength range and a slit of 1.2 arcsec, yielding a spectral resolving power of about 560 at the central wavelength. We acquired our targets in parallactic angle with the Sloan z-b band filter owing to their faintness in the optical. We employed on-source integrations with the individual exposure times provided in Table 2, with two to four repeats shifted along the slit by 10 to 15 arcsec, depending on the crowding of the field to allow for sky subtraction. As part of programme GTC55-19A, we also observed a nearby brown dwarf spectral standard with a clear lithium absorption, namely DENIS 1228 (Martin et al. 1997, 1999).

We reduced the data under the Image Reduction and Analysis Facility (IRAF) environment (Tody et al. 1993) in a standard manner. First, we median-combined the bias and flat fields taken during the afternoon, which we removed from the raw images. We extracted optimally each individual spectrum choosing the aperture and sky regions. We calibrated the spectra in wavelength with HgAr, xenon, and neon lamps with a rms better than 0.3 Å before averaging the spectra to produce the final spectra shown in Fig. 4. We flux calibrated the 1D spectra with the response functions derived from two spectrophotometric standard stars: Hilt 600 (B1; Pancino et al. 2012) and Ross 640 (DZA5.5; Greenstein & Trimble 1967; Harrington & Dahn 1980; Wesemael et al. 1993) for programmes GTC47-18A and GTC55-19A, respectively. We did not correct for the second-order contamination so the flux calibration is solely valid up to 9500 Å.

3.2. Spectral typing

We normalised the OSIRIS spectra between 8240 Å and 8260 Å to compare with reference ultra-cool dwarfs of known spectral type because this wavelength range is located in a pseudo-continuum region in late-M dwarfs (Martin et al. 1996). Spectral types were assigned to the targets by visual comparison with field late-M and early-L dwarfs from the SDSS database (Bochanski et al. 2007; Schmidt et al. 2010). A comparison of the spectra of one of our targets with the SDSS templates is shown in Fig. 5. The spectral types adopted in this work, and those from the literature for the sources in common, are listed in Table 3. We infer an optical spectral type of M9.0 ± 0.5 for cbd34 (= T176) fully consistent with the infrared spectral types derived independently by Casewell et al. (2014) and Tang et al. (2018). This object is the warmest member candidate in our list of targets with GTC/OSIRIS optical spectra. We classify cbd10 as a M9.5 ± 0.5 dwarf, which was lacking a spectrum in Casewell et al. (2014). We classify optically T159 as a L2.0 ± 0.5 dwarf, again in agreement with the infrared spectral type in Table 4 of Tang et al. (2018). Its optical spectrum is similar to cbd67, which was previously classified as L1 in the near-infrared by Casewell et al. (2014), and to ComaBer 4, 5, and 7 to which we assign the same spectral type. The coolest object in our spectroscopic sub-sample is T191, classified optically as a L2.5 ± 0.5, although we find it to be 1.5 sub-types earlier than the infrared classification of Tang et al. (2018, their Table 4).

1 IRAF is distributed by the National Optical Astronomy Observatories, which is operated by the Association of Universities for Research in Astronomy (AURA) under cooperative agreement with the National Science Foundation
Fig. 2. Colour–magnitude diagrams with optical and infrared photometry from the GCS and Pan-STARRS surveys showing all sources common to UKIDSS GCS, Pan-STARRS DR1, and SDSS DR12 (small grey dots) along with iK candidates selected photometrically along the line of sight of Coma Ber. Overplotted are candidates from Casewell et al. (2006, 2014), Tang et al. (2018), and our study as red squares, orange triangles, and blue asterisks, respectively. The 500 Myr BT-Settl isochrones (Baraffe et al. 2015) are added as dashed orange lines and members in the Hyades (Hogan et al. 2008; Bouvier et al. 2008; Goldman et al. 2013); the sequence of field ultra-cool dwarfs with known distances (magenta dashed curve) is shown for comparison in the diagrams for which suitable photometric data are available. The selection cuts to identify photometric candidate members in Coma Ber are shown as green dashed lines.
but not in the Coma Ber targets. We did not detect the Li reference lithium L dwarf DENIS1228 (Martín et al. 1997, 1999), whose NaI doublet clearly stands out from the noise in our reference spectrum of DENIS J1228 using the IRAF task fxcor over the spectral range 8100–10000 Å. Error bars were derived from Gaussian fits to the correlation function. We derived heliocentric RV corrections with the IRAF task rvcor. Instrumental zero-point correction was applied using a RV of 4 km s\(^{-1}\) for DENIS J1228 (Martín et al. 1997). The measured RVs obtained for our targets and their uncertainties are provided in Table 3. The RV values of all but one of the Coma Ber targets are consistent within the error bars with the mean RV of the cluster (\(-0.52\) km s\(^{-1}\)) provided by Gaia DR2 (Gaia Collaboration 2018). The exception is ComaBer7, which has a larger RV value of 62 ± 16 km s\(^{-1}\); this deviates from the cluster RV by more than three times the uncertainty.

Since cbd67 has not been deemed to be a bona fide member in Coma Ber because it does not have consistent proper motion (Tang et al. 2018), and ComaBer7 has a larger RV value than expected for a member in the cluster, we did not include these objects in the subset of confirmed cluster members. Therefore, only cbd10/34, ComaBer4/5, and T159/191 are retained as bona fide cluster members confirmed by our RV analysis. We note that ComaBer5 does not have membership confirmation by proper motion.

### 3.4. Pseudo-equivalent width measurements

We searched for the presence of Li I in absorption at 6707.8 Å in the GTC/OSIRIS spectra. A zoom on the Li I spectral region is shown in Fig. 6 for a representative subset of our sample. The Li I resonance doublet clearly stands out from the noise in our reference lithium L dwarf DENIS1228 (Martín et al. 1997, 1999), but not in the Coma Ber targets. We did not detect the Li I feature in any of the Coma Ber spectra. Signal-to-noise ratios (S/N) in a spectral region adjacent to the Li I spectral region were measured with the spot task in IRAF, and are given in Table 2. This region is the same as that used in Martín et al. (2018). The S/N values measured by us in the Coma Ber targets tend to be slightly lower than those reported by Martín et al. (2018) for Hyades targets, and hence our uncertainties in pEW measurements are larger.

From these data we can only impose upper limits on the Li I pseudo-equivalent width (pEW) of the Coma Ber targets. Those upper limits, together with pEW measurements or upper limits on the emission of H\(_\alpha\) and other atomic lines of interest (CsI, NaI, and RbI), are provided in Table 4. The pEW values were estimated independently by each author using the task spot in the IRAF environment. The mean value of each measurement was adopted and the error bar reflects the dispersion in the values obtained. The pEW values of the Cs I and Li I features obtained from our spectrum of DENIS1228 are consistent within the measurement uncertainties with those reported by Kirkpatrick et al. (1999) and Martín et al. (1999). On the other hand, for the Na I doublet our value is significantly lower than that reported by Martín et al. (1999). This could be because we partially resolved the Na I doublet, whereas it is completely blended in the KeckII data presented in Martín et al. (1999), and to contamination by telluric absorption in the red part of the feature.

Weak H\(_\alpha\) in emission is detected in 3 out of the 6 Coma Ber members. The frequency of H\(_\alpha\) emitters among Coma Ber M9–L2.5 objects (50%) is higher than among high-gravity field dwarfs in the same range of spectral sub-classes (8 out of 34; 23.5%) (Martín et al. 2010), suggesting that chromospheric activity is stronger in the Coma Ber sub-stellar population because it is younger than the field.

Low-gravity field dwarfs with spectral sub-classes from M9 to L0 are thought to have ages younger than about 100 Myr. They have Na I pEW values below 4 Å, and H\(_\alpha\) pEW values stronger than pEW = −14 Å (Martín et al. 2010). None of the targets we observed have as weak Na I and as strong H\(_\alpha\) emission as low-gravity field dwarfs, indicating that they are older, high-gravity ultra-cool dwarfs.

### 4. Lithium depletion and the age of Coma Ber

The upper limits to the pEW of the Li I resonance doublet reported in Table 4, were converted to Li abundances using the method described in Martín et al. (2018), and the same initial Li abundance of log N(Li) = 3.3 as in the Hyades, which is thought to be representative of the cosmic Li content in newly born stars (Martín et al. 1994b; Martín 1997).

Since Coma Ber is not much younger than the Hyades, it is likely that the L-type members are BDs, but this is not guaranteed for the late-M members. In the following discussion, we retain only the bona fide sub-stellar cluster members, that is the L-type brown dwarfs confirmed by strong RVs. As discussed by Martín et al. (2018), it is justified to use the calibrations for field L dwarfs of known distance to calculate the bolometric luminosities (log L bol/L\(_\odot\)) and effective temperatures (T\(_\text{eff}\)) from the spectral types obtained by us for the cluster members. The values obtained using the calibrations from Filippazzo et al. (2015) are provided in Table 5.

The lack of Li detection implies that the Coma Ber BDs have depleted significant amounts of this light element, which in turn can be used to derive constraints on the age of the cluster using evolutionary models. In our previous work in the Hyades (Martín et al. 2018), we found that there is good agreement between the Li depletion age constraints and other parameters such as luminosity and temperature for the models by
The limit obtained from the L2.5 member (T191) is 50 Myr.

Notes. The ID number, coordinates in sexagesimal format from UKIDSS GCS, and the infrared and optical photometry from UKIDSS GCS DR9, Pan-STARRS DR1, and SDSS DR12 are listed. Top panel: four photometric candidates in common with earlier studies (Casewell et al. 2014; Tang et al. 2018). Middle panel: eight photometric candidates with proper motion consistent with the mean motion of the cluster. Bottom panel: the remaining 22 photometric candidates. Known sources are #2963 = T191, #2816 = T159, #2838 = cdb67, and #2868 = cdb10. New objects with GTC spectroscopy are ComaBer 4 = #2938, ComaBer 5 = #2975, and ComaBer 7 = #2857. The full table is available at the CDS.

Table 2. Log of the GTC OSIRIS spectroscopic observations.

<table>
<thead>
<tr>
<th>RA</th>
<th>Dec</th>
<th>Z</th>
<th>J</th>
<th>H</th>
<th>K</th>
<th>Ps1</th>
<th>Ps2</th>
<th>Ps3</th>
<th>Ps4</th>
<th>Sdss1</th>
<th>Sdss2</th>
<th>Sdss3</th>
<th>Sdss4</th>
<th>Sdss5</th>
<th>Sdss6</th>
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<tbody>
<tr>
<td>hh:mm:ss.s</td>
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</table>

Coma Ber have ranged from 300 Myr to 1000 Myr (Tsvetkov 1989). For example, Kraus & Hillenbrand (2007) used an age of 400 Myr in their study of the low-mass population. The lower limit on the age derived in this work restricts the allowed range of ages for Coma Ber to lie between 550 Myr and 1000 Myr, and hence we propose a revised age estimate of 730 ±30 Myr.
which is consistent with the age estimates in the range 700–800 Myr proposed by Tang et al. (2018, 2019) from an analysis of a few post-main-sequence stars.

A more precise age estimate for this cluster could be derived from Li detection in members that are cooler than those studied in this work. We plan to carry out a search for fainter Coma Ber members using the Euclid wide survey in the framework of the project Independent Legacy Science on ultra-cool dwarfs, which was selected by ESA in 2012. According to the Euclid specifications, the wide survey should reach about 5 mag deeper in optical and near-infrared passbands than the surveys that we have used in this work. If the age of Coma Ber is as old or older than that of the Hyades, the LDB should be located at spectral type later than L3. Li has been detected in L3.5–L5 members in the Hyades (Martín et al. 2018; Lodieu et al. 2018b). Similar observations in L dwarfs in Coma Ber would be challenging but not unfeasible and are critical to refine the age of Coma Ber using the sub-stellar Li boundary method.

Coma Ber is the second open cluster closest to us, and also the second open cluster known for which the LDB age is older than 500 Myr. In Table 6 we put our LDB results for Coma Ber in context with previous results for other open clusters older than 20 Myr. We note that the results reported in this work, together with those in the Hyades, have significantly extended the range of applicability of the LDB method.

As shown in Table 6, in which the spectral type of the objects where Li re-emerges in different open clusters is listed in column 3, the LDB evolves from mid-M spectral types at very

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**Table 3.** Spectral types and RVs derived in this work.

<table>
<thead>
<tr>
<th>Name</th>
<th>SpT Literature</th>
<th>SpT This work</th>
<th>RVs km s⁻¹</th>
</tr>
</thead>
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<tr>
<td>cbd34</td>
<td>M9</td>
<td>M9.0 ± 0.5</td>
<td>−2 ± 38</td>
</tr>
<tr>
<td>cbd10</td>
<td>L1</td>
<td>L2.0 ± 0.5</td>
<td>−18 ± 35</td>
</tr>
<tr>
<td>cbd67</td>
<td>L2.0</td>
<td>L2.0 ± 0.5</td>
<td>16 ± 24</td>
</tr>
<tr>
<td>ComaBer4</td>
<td>L2.0</td>
<td>L2.0 ± 0.5</td>
<td>2 ± 15</td>
</tr>
<tr>
<td>ComaBer5</td>
<td>L2.0</td>
<td>L2.0 ± 0.5</td>
<td>62 ± 16</td>
</tr>
<tr>
<td>T159</td>
<td>L2</td>
<td>L2.0 ± 0.5</td>
<td>10 ± 21</td>
</tr>
<tr>
<td>T191</td>
<td>L4</td>
<td>L2.5 ± 0.5</td>
<td>−1 ± 14</td>
</tr>
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</table>

**Notes.** Spectral types from the literature come from Casewell et al. (2014) and Tang et al. (2018). Targets are ordered from earlier to later spectral sub-classes.
young ages (20–50 Myr) to mid-L dwarfs at more mature ages (600–700 Myr). Since BDs keep cooling down with increasing time, the LDB method can still be applied to even older open clusters, moving groups, associations, or multiple stellar systems. Applying this method to these sources will be harder however because in Coma Ber we are already reaching the practical limit of what can be done with a 10 m class telescope in a reasonable amount of observing time. The new generation of larger optical telescopes will be needed to extend this work to more distant and/or older clusters such as Praesepe, whose BD candidates have already been identified in this cluster (Magazzù et al. 1998; Wang et al. 2011), and whose age is similar to Coma Ber; this cluster is located more than twice as far away, however (Lodieu et al. 2019).

The LDB method is orthogonal to other dating methods, such as isochrone fitting and gyro-chronology, and tends to provide rather precise values that could be useful to constrain the wider range of estimates obtained from various stellar clocks. The validity of the LDB now extends for over a factor of 3 in mass and over a factor of 30 in age, and provides a promising method to calibrate traditional models of evolved intermediate-mass stars, low-mass pre-main-sequence stars, and young main-sequence stars.

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Table 4. Pseudo EWs of atomic lines in targets observed with GTC/OSIRIS.

<table>
<thead>
<tr>
<th>Name</th>
<th>H$_\alpha$</th>
<th>Li1</th>
<th>Rb1</th>
<th>Rb1</th>
<th>Na1</th>
<th>Cs1</th>
<th>Cs1</th>
</tr>
</thead>
<tbody>
<tr>
<td>cbd34</td>
<td>6562.8 Å</td>
<td>6707.8 Å</td>
<td>7800.3 Å</td>
<td>7947.6 Å</td>
<td>8190 Å</td>
<td>8521.1 Å</td>
<td>8943.0 Å</td>
</tr>
<tr>
<td>cb10</td>
<td>−2.6 ± 0.8</td>
<td>&lt;1.0</td>
<td>1.0 ± 0.3</td>
<td>2.0 ± 0.3</td>
<td>5.5 ± 0.2</td>
<td>1.5 ± 0.5</td>
<td>1.8 ± 0.5</td>
</tr>
<tr>
<td>cb67</td>
<td>−2.1</td>
<td>&lt;1.1</td>
<td>2.3 ± 0.6</td>
<td>1.9 ± 0.7</td>
<td>5.8 ± 0.9</td>
<td>3.2 ± 0.6</td>
<td>2.9 ± 0.4</td>
</tr>
<tr>
<td>ComaBer4</td>
<td>−5.5 ± 0.8</td>
<td>&lt;3.3</td>
<td>4.0 ± 1.5</td>
<td>3.5 ± 0.5</td>
<td>6.7 ± 0.5</td>
<td>2.5 ± 0.5</td>
<td>2.5 ± 0.5</td>
</tr>
<tr>
<td>ComaBer5</td>
<td>−2.0 ± 1.5</td>
<td>&lt;1.5</td>
<td>2.4 ± 0.2</td>
<td>1.5 ± 0.5</td>
<td>5.1 ± 0.2</td>
<td>3.1 ± 0.3</td>
<td>1.7 ± 0.2</td>
</tr>
<tr>
<td>ComaBer7</td>
<td>&gt;−4.0</td>
<td>&lt;3.0</td>
<td>5.0 ± 0.5</td>
<td>3.4 ± 0.2</td>
<td>6.1 ± 0.3</td>
<td>2.9 ± 0.5</td>
<td>1.3 ± 0.3</td>
</tr>
<tr>
<td>T159</td>
<td>&gt;−4.0</td>
<td>&lt;2.0</td>
<td>3.1 ± 0.3</td>
<td>2.3 ± 0.5</td>
<td>5.5 ± 0.3</td>
<td>1.8 ± 0.5</td>
<td>1.9 ± 0.2</td>
</tr>
<tr>
<td>T191</td>
<td>&gt;−1.5</td>
<td>&lt;1.2</td>
<td>4.9 ± 0.4</td>
<td>4.6 ± 0.9</td>
<td>4.7 ± 0.3</td>
<td>2.3 ± 0.7</td>
<td>3.0 ± 0.4</td>
</tr>
<tr>
<td>DENIS1228</td>
<td>−1.75 ± 0.25</td>
<td>2.6 ± 0.6</td>
<td>4.7 ± 1.5</td>
<td>6.5 ± 0.5</td>
<td>4.9 ± 0.3</td>
<td>4.0 ± 0.3</td>
<td>4.3 ± 0.2</td>
</tr>
</tbody>
</table>

Table 5. Basic parameters and Li abundances for RV confirmed sub-stellar members in Coma Ber.

<table>
<thead>
<tr>
<th>Name</th>
<th>SpT</th>
<th>log($L_{bed}/L_\odot$)</th>
<th>$T_{eff}$ (K)</th>
<th>log N(Li)</th>
<th>Age (Myr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ComaBer4</td>
<td>L2.0 ± 0.5</td>
<td>−3.83 ± 0.13</td>
<td>1959 ± 113</td>
<td>&lt;2.4</td>
<td>&gt;480</td>
</tr>
<tr>
<td>ComaBer5</td>
<td>L2.0 ± 0.5</td>
<td>−3.83 ± 0.13</td>
<td>1959 ± 113</td>
<td>&lt;1.8</td>
<td>&gt;500</td>
</tr>
<tr>
<td>T159</td>
<td>L2.0 ± 0.5</td>
<td>−3.83 ± 0.13</td>
<td>1959 ± 113</td>
<td>&lt;2.0</td>
<td>&gt;490</td>
</tr>
<tr>
<td>T191</td>
<td>L2.5 ± 0.5</td>
<td>−3.90 ± 0.13</td>
<td>1890 ± 113</td>
<td>&lt;1.5</td>
<td>&gt;550</td>
</tr>
</tbody>
</table>
Fig. 7. Evolutionary tracks (effective temperature \(T_{\text{eff}}\) and luminosity) from the models by Baraffe et al. (2015) for VLM stars and BDs as a function of age. Masses and predicted Li depletion factors are labelled. The non-detection of Li in the Coma Ber member candidates studied in this work impose lower limits on the cluster age. The limit coming from the L2 candidates is depicted as the upper red triangle and horizontal line, and the limit obtained from the L2.5 object (T191) corresponds to the lower triangle and horizontal line in red.

Table 6. Li depletion boundary (LDB) in open clusters older than 20 Myr, ordered by increasing distance.

<table>
<thead>
<tr>
<th>Name</th>
<th>d pc</th>
<th>SpT</th>
<th>Age (LDB)</th>
<th>Age (Other)</th>
<th>Mass (M_\odot)</th>
<th>Ref.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hyades</td>
<td>47</td>
<td>L4</td>
<td>650 ± 70</td>
<td>570–900</td>
<td>0.065</td>
<td>Martín et al. (2018)</td>
</tr>
<tr>
<td>Coma Ber</td>
<td>87</td>
<td>&gt;L2.5</td>
<td>&gt;550</td>
<td>300–1000</td>
<td>&lt;0.07</td>
<td>This work</td>
</tr>
<tr>
<td>Pleiades</td>
<td>130</td>
<td>M6.5</td>
<td>112 ± 5</td>
<td>70–160</td>
<td>0.075</td>
<td>Dahn (2015)</td>
</tr>
<tr>
<td>IC 2391</td>
<td>146</td>
<td>M5</td>
<td>50 ± 5</td>
<td>30–75</td>
<td>0.12</td>
<td>Barrado y Navascués et al. (2004)</td>
</tr>
<tr>
<td>IC 2602</td>
<td>152</td>
<td>M5.5</td>
<td>46 ± 6</td>
<td>25–70</td>
<td>0.12</td>
<td>Dobbie et al. (2010)</td>
</tr>
<tr>
<td>Alpha Per</td>
<td>190</td>
<td>M6.5</td>
<td>85 ± 10</td>
<td>50–70</td>
<td>0.08</td>
<td>Barrado y Navascués et al. (2004)</td>
</tr>
<tr>
<td>Blanco 1</td>
<td>207</td>
<td>M7</td>
<td>126 ± 14</td>
<td>150–500</td>
<td>0.072</td>
<td>Juarez et al. (2014)</td>
</tr>
<tr>
<td>IC 4665</td>
<td>385</td>
<td>M4</td>
<td>28 ± 5</td>
<td>30–100</td>
<td>0.24</td>
<td>Manzi et al. (2008)</td>
</tr>
<tr>
<td>NGC 2547</td>
<td>430</td>
<td>M4</td>
<td>35 ± 4</td>
<td>20–80</td>
<td>0.17</td>
<td>Jeffries &amp; Oliveira (2005)</td>
</tr>
</tbody>
</table>
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References