IDENTIFICATION OF THE LITHIUM DEPLETION BOUNDARY AND AGE OF THE SOUTHERN OPEN CLUSTER BLANCO 1

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ABSTRACT

We present results from a spectroscopic study of the very low mass members of the Southern open cluster Blanco 1 using the Gemini-N telescope. We obtained intermediate resolution (R ~ 4400) GMOS spectra for 15 cluster candidate members with I ~ 14–20 mag, and employed a series of membership criteria—proximity to the cluster’s sequence in an I/1–K_s color–magnitude diagram (CMD), kinematics agreeing with the cluster systemic motion, magnetic activity as a youth indicator—to classify 10 of these objects as probable cluster members. For these objects, we searched for the presence of the Li I λ6708 Å feature to identify the lithium depletion boundary (LDB) in Blanco 1. The I/1–K_s CMD shows a clear mass segregation in the Li distribution along the cluster sequence; namely, all higher mass stars are found to be Li poor, while lower mass stars are found to be Li rich. The division between Li-poor and Li-rich (i.e., the LDB) in Blanco 1 is found at I = 18.78 ± 0.24 and I – K_s = 3.05 ± 0.10. Using current pre-main-sequence evolutionary models, we determine an LDB age of 132 ± 24 Myr. Comparing our derived LDB age to upper-main-sequence isochrone ages for Blanco 1, as well as for other open clusters with identified LDBs, we find good chronometric consistency when using stellar evolution models that incorporate a moderate degree of convective core overshoot.

Key words: open clusters and associations: general – open clusters and associations: individual (Blanco 1) – stars: evolution – stars: fundamental parameters

Online-only material: color figures

1. INTRODUCTION

As pre-main-sequence (PMS) low-mass stars (<0.6 M_⊙) approach the zero-age main sequence, their natal lithium content is rapidly destroyed by proton burning in regions where their interior temperature reaches above ~2.5 × 10⁶ K. Since the central temperature of a young star is a sensitive function of stellar mass and age (Bildsten et al. 1997; Ushomirsky et al. 1998), determining the mass, or equivalently the luminosity, at which stars in an open cluster fully deplete their initial lithium content allows us to measure the cluster age—the so-called lithium depletion boundary (LDB) method. The LDB stellar dating technique is model dependent; however, unlike traditional isochrone modeling of the color–magnitude diagram (CMD), different evolutionary LDB models yield very similar (∼±10%) ages (Burke et al. 2004). It is this model insensitivity that makes LDB ages so valuable, not only as a vital tool to define and constrain models of stellar evolution, but more importantly in assessing missing input physics in the more widely used isochrone modeling techniques.

LDB ages are inherently difficult to measure due to the necessity of procuring spectra of very faint, low-mass stars that have not yet depleted their natal lithium, typically a cluster’s mid- to late-M dwarfs. Furthermore, the technique is most sensitive to young stellar ages, ~10–250 Myr. These limitations have resulted in only six open clusters so far having LDB age determinations: Pleiades (126 ± 11 Myr; Stauffer et al. 1998; Burke et al. 2004), α Persei (90 ± 10 Myr; Stauffer et al. 1999), IC 2391 (50 ± 5 Myr; Barrado y Navascués et al. 1999, 2004), NGC 2547 (35 ± 4 Myr; Jeffries & Oliveira 2005), IC 4665 (27 ± 5 Myr; Manzi et al. 2008), and IC 2602 (46 ± 6 Myr; Dobbie et al. 2010). In this Letter, we present initial results from our campaign to identify the LDB in the open cluster Blanco 1.

Blanco 1 is a relatively young (50–150 Myr; Panagi & O’Dell 1997; Moraux et al. 2007), nearby Southern open cluster (209 pc; van Leeuwen 2009) of particular astrophysical interest due to its high Galactic latitude (b = −79°), and its comparable age to the well-studied Pleiades cluster. Considerable interest in the cluster has been driven by its reported metal-rich nature ([Fe/H] = +0.23; Edvardsson et al. 1995), although a more recent determination now makes the cluster of near-solar composition ([Fe/H] = +0.04 ± 0.04; Ford et al. 2005). Differences in the updated metallicity of Blanco 1 are attributed to the adoption of significantly cooler stellar temperatures that are consistent with photometric and spectroscopic constraints. A combination of the cluster’s systemic motion, distance below the Galactic plane (∼250 pc), and estimated age (50–150 Myr) suggests it was formed in or very near to the Galactic plane, and has subsequently moved to its current Galactic position. Its Galactic location makes it a highly attractive target for LDB study due its low level of field star contamination, making membership selection relatively straightforward (e.g., Mermilliod et al. 2008).

2. TARGET SELECTION, OBSERVATIONS, AND DATA REDUCTION

Recently, Moraux et al. (2007, hereafter M07) assembled an infrared photometric catalog of the very low mass (VLM) members of Blanco 1. In order to identify brown dwarf candidates in the cluster, they observed 17 photometric candidate
members having \( I \sim 18.0–20.0 \) with low-resolution \((R \sim 1000)\) spectroscopy using the VLT FORS2 and KECK LRIS instruments. Using a detailed spectral analysis technique, they identified 15/17 objects as probable cluster low-mass members. Unfortunately, their spectral resolution level prejudiced measurement of the location of the LDB for Blanco 1. However, M07’s list of probable members provides us with a robust target list for our LDB study, as the expected luminosity of the LDB in a cluster of age \( \sim 100 \) Myr and at a distance of \( \sim 200 \) pc, corresponds to \( I \simeq 19 \) (Burke et al. 2004).

We obtained spectra during 2009 October 11–19 of seven probable Blanco 1 members listed in M07 with the Gemini Multi-Object Spectrograph (GMOS) in queue schedule mode on the Gemini-North telescope (Hook et al. 2004). The targets have an apparent magnitude range bracketing the expected cluster’s LDB, i.e., \( I = 18.3–19.7 \). We observed these Blanco 1 candidates in six separate \( 5.5 \times 5.5 \) fields using 1” slitlets for our target stars \((R \sim 4400)\), employing the R831 (G5302) grating blazed at 7570 Å, with a blue-blocking OG515 (G0306) filter. This instrument setup produced spectra with a wavelength range of \( \sim 5700–8000 \) Å with a resolution of 0.67 Å per pixel. Exposure times were set between 65 and 110 minutes, depending on the faintest target in each field, resulting in spectra with signal-to-noise ratio \((S/N)\) per pixel of \( \sim 10 \) and \( \sim 500 \) for the faintest and brightest targets, respectively. Exploiting the GMOS multi-object mode, we used a recent optical survey, performed using the SMARTS 1.0 m telescope at CTIO, to select an additional eight stars with \( I_c \sim 13.0–17.5 \) found in the six GMOS fields that we identified as photometric candidate members from their location near the cluster sequence in an optical CMD (see D. J. James et al. 2011, in preparation). Most of these stars had no previous ancillary evidence for cluster membership because their brightness falls below the faintness limit of most previous membership studies for the cluster (e.g., proper motions are currently limited to \( I_e = 14.5 \); D. J. James et al. 2011, in preparation). Not only do the inclusion of these stars in our program increase the total number of known Blanco 1 members, but they also help us identify the magnitude range of stars that have already depleted their lithium content, thus allowing for a more confident LDB measurement. In addition to these primary target stars, GJ 905, a dM6 radial-velocity (RV) standard star (Nidever et al. 2002), was also observed with the identical instrument setup as our Blanco 1 objects. We reduced all of our GMOS spectra using the standard reduction routines available in the IRAF Gemini–GMOS package,\(^5\) including bias removal, aperture extraction, and wavelength calibration.

### 3. ANALYSIS

In Table 1, we list the 15 photometric cluster candidate members observed as part of our GMOS observing program. For each object, we include positions, photometric properties, RVs, \( H \alpha \) equivalent widths (EWs), whether we detected Li\( \alpha \) absorption at 6708 Å, and each object’s membership status. Positions are taken from the Two Micron All Sky Survey \((2MASS)\) catalog (Skrutskie et al. 2006) for stars with \( I < 17.5 \), or Moraux et al. for \( I > 17.5 \). For \( I > 17.5 \), no individual photometric uncertainties were published in Moraux et al.\(^6\)

\( a \) Targets are from: JCO–SMARTS optical survey; CFHT–BL–Moraux et al. (2007).

\( b \) 12000.0 Coordinates.

\( c \) The \( K_s \) values are from either the 2MASS catalog for stars with \( I < 17.5 \), or Moraux et al. for \( I > 17.5 \). For \( I > 17.5 \), no individual photometric uncertainties were published in Moraux et al.\(^6\)

\( d \) Positive values indicate the line is in emission.

\( e \) Y–Li absorption detected at the \( \sim 3\sigma \) level, N–Li absorption not detected above \( 1\sigma \).

\( f \) Y—confirmed cluster member, N—either cluster non-member or currently undetermined.

\( g \) I<catalogs. For the fainter stars \((I > 17.5)\) (i.e., those stars taken from our optical catalog), and for fainter stars we use the positions published in M07.

Photometric data for our Blanco 1 targets are collected from two sources: for stars with \( I < 17.5 \) (i.e., those indicated with a “JCO” prefix in Table 1), we use the \( I \) magnitudes from our recent photometric survey of several southern open clusters (e.g., see Cargile et al. 2009; Cargile & James 2010; D. J. James et al. 2011, in preparation), and \( K_s \) photometry is from the 2MASS survey (Skrutskie et al. 2006). Uncertainties on individual photometric data points are taken from the original catalogs. For the fainter stars \((I > 17.5)\), we use the \( I \) and

\( i \) IRAF, in our case through http://iraf.net, is distributed by the National Optical Astronomy Observatory, which is operated by the Association of Universities for Research in Astronomy, Inc., under cooperative agreement with the National Science Foundation.
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average photometric error of ∼0.04 and ∼0.03 mag for I and Ks, respectively. Therefore, we adopt these average uncertainties for all of the stars we include from the M07 catalog (i.e., I > 17.5).

RVs for each of Blanco 1 targets (see Table 1) were measured by cross-correlating the GMOS spectra with the RV standard star GJ 905. Uncertainties on these RVs are relatively large (∆RV ∼ 5–15 km s⁻¹), which is due to the low S/N of the target spectra and the moderate resolution of our observations.

We measure the EWs of the Hα feature for each GMOS spectra using the SPLot task in IRAF. EWs were determined using a Gaussian-line profile, modeled using a linear normalization to the pseudo-continuum calculated from wavelength regions flanking the Hα feature. Uncertainties for EWs have been approximated using the formula \( \Delta \text{EW} \sim 1.5 \times \sqrt{\text{FWHM} \times \frac{p}{(S/N)}} \), where FWHM, \( p \), and S/N are the FWHM of the Gaussian, the pixel dispersion scale in Å, and the S/N, respectively (Cayrel 1988). We include the 1σ errors on the Hα EW measurements in Table 1.

### 3.1. Membership Selection

In order to classify our target stars as cluster members of Blanco 1, we consider three different membership criteria: (1) photometry consistent with the cluster sequence in an \( I/I - K_s \) CMD, (2) RVs must be within 1σ of the cluster systemic velocity (∼+6 km s⁻¹) and accounting for the observed ±4 km s⁻¹ velocity dispersion in the cluster (Mermilliod et al. 2008), and (3) Hα line EWs must be comparable to similar mass stars in the similar age Pleiades cluster.

In Figure 1, we plot the CMD for all 15 objects observed in our GMOS program. Of these, 14 have photometry consistent, within 3σ of their photometric uncertainty, of the empirical, single-star \( I/I - K_s \) Pleiades cluster sequence from Stauffer et al. (2007) shifted to the distance to Blanco 1 (207 ± 12 pc; van Leeuwen 2009). We also take into account a possible 0.1 mag offset of the cluster sequence in order to account for natural variability in young stars. We further rejected two targets due to their RV being inconsistent with single-star membership to the cluster. In both cases, the rejected RV differed from the cluster systemic velocity by many σ; however, we note that these rejected objects might in fact be cluster members in short-period binary systems. Further, RV measurements are required to confirm their binary nature. We reject an additional two stars, JCO-F9-229 and JCO-F9-123, for not having significant Hα emission, i.e., \( \text{EW}(\text{H}\alpha) > +0.5 \) Å, although they are photometric members and have RVs consistent with cluster membership. These stars may be cluster members with abnormally low levels of Hα emission, however follow-up observations are necessary to verify these stars as bona fide cluster members. Nevertheless, in order to be consistent in our membership selection, and to ensure the lowest probability of contamination in our membership catalog of VLM Blanco 1 stars, we presently classify these two stars as cluster non-members. Therefore, in summary, we have identified 10 high-fidelity VLM members of Blanco 1, out of the 15 observed GMOS targets.

### 3.2. Identification of Blanco 1 LDB

Previous studies have shown that young, VLM (spectral-type M0–M9), Li-rich stars in similar-aged open cluster have \( \text{EW}(\text{Li}) \sim 1 \) Å (e.g., Pleiades, Stauffer et al. 1998; α Persei, Stauffer et al. 1999; Barrado y Navascués et al. 2004). In fact, the Li \( \sim 6708 \) Å line is expected to saturate at ∼0.6–0.7 Å according to the curves of growth given in Zapatero Osorio et al. (2002). Also, the saturated nature of the Li \( i \) feature means its absence indicates significant Li depletion has occurred (e.g., 90% Li depletion only reduces the EW(Li) by a factor of ∼2 according to Zapatero Osorio et al. 2002). Therefore, the presence or absence of the Li \( i \) \( \sim 6708 \) Å feature is an excellent indicator of PMS Li-depletion in stars. Unfortunately, the combination of a low S/N for our faintest stars and the medium resolution of GMOS makes a direct EW measurements of the Li feature in our Blanco 1 spectra very uncertain. Therefore, we employ a comparative analysis approach to detect the presence of Li in our Blanco 1 objects.

Figure 2 shows the spectral region around the Li \( i \) doublet at \( \sim 6708 \) Å for 9 Blanco 1 cluster members (the early spectral-type cluster member JCO-F18-88 is not plotted due to the lack of a K-dwarf spectral template). For comparison, we also plot spectra of similar spectral-type stars from the M-dwarf template catalog from the Sloan Digital Sky Survey (SDSS; Bochanski et al. 2007). These templates were produced by averaging over ∼4000 SDSS stellar spectra for spectral-types dM0–dL0. Due to the observing strategy of the SDSS, the majority of the combined spectra used for these templates are field M-dwarfs, and therefore are expected to be old enough (>0.5 Gyr) to have destroyed their initial lithium—except for the dL0 template which is expected to be below the mass necessary to reach a central Li-depleting temperature. We matched the SDSS spectra by determining the closest match to the major absorption features and overall shape of the pseudo-continuum of the GMOS spectra.

![Figure 1.](image)

**Figure 1.** Intrinsic \( I/I - K_s \) CMD for 15 Blanco 1 candidates. Stars rejected as single-star cluster members are identified as black crosses. Photometric error bars are 1σ. VLM cluster members with significant Li absorption are indicated as filled red squares, and Li-poor members are shown as open blue circles. The Pleiades single-star locus is plotted as a purple solid line. A zoomed-in region around the LDB is plotted in the inset. The solid box shows the probable region of the LDB for Blanco 1. Also plotted are BCAH98 predicted constant luminosity loci (dotted lines) corresponding to the given LDB ages. (A color version of this figure is available in the online journal.)
Below each Blanco 1 spectrum is a subplot of the moving integrated residual for the GMOS and SDSS spectra. These data points are derived by integrating over the GMOS spectra around the Li 6708 Å feature (red dotted line) are plotted for nine confirmed VLM members of Blanco 1 (blue solid line). For comparison, scaled spectra of similar spectral-type SDSS templates are also plotted (green dashed line). Below each VLM spectra is the moving integrated residual (GMOS–SDSS) with σ levels noted. Blanco 1 identifiers with I band magnitudes (black), and SDSS template spectral-types (green) are given at the top right of each panel. The early spectral-type star JCO-F18-88 is not plotted. (A color version of this figure is available in the online journal.)

Figure 2. GMOS spectra around the Li 6708 Å feature (red dotted line) are plotted for nine confirmed VLM members of Blanco 1 (blue solid line). For comparison, scaled spectra of similar spectral-type SDSS templates are also plotted (green dashed line). Below each VLM spectra is the moving integrated residual (GMOS–SDSS) with σ levels noted. Blanco 1 identifiers with I band magnitudes (black), and SDSS template spectral-types (green) are given at the top right of each panel. The early spectral-type star JCO-F18-88 is not plotted. (A color version of this figure is available in the online journal.)

Below each Blanco 1 spectrum is a subplot of the moving integrated residual for the GMOS and SDSS spectra. These data points are derived by integrating over the GMOS–SDSS residual in a moving 5 Å window, with a moving step-size of 2 Å. By integrating over a moving window, we average out the small difference between the GMOS and SDSS spectra (e.g., different spectral resolutions), and provide a better description of the significant deviation between the GMOS and SDSS spectra. The σ levels are derived from the r.m.s. of the residual outside of a 10 Å window centered on the Li 6708 Å feature. We note that CFHT-BL−49 is best matched with the dL0 template, which still retains its natal Li content; therefore, as expected the residual does not show a significant difference at 6708 Å.

A clear trend is present when looking at the distribution of Li-absorption in VLM Blanco 1 stars. Namely, brighter (higher mass) Blanco 1 members are ubiquitously Li poor; any observed Li absorption at 6708 Å is not significant beyond 1σ. This suggests these stars have already gone through their PMS Li burning stage. Fainter (lower mass) Blanco 1 VLM stars are all observed to be Li rich with Li absorption detections at or above ~3σ. The transition from Li poor to Li rich is bracketed by CFHT-BL−24 (I = 18.54 ± 0.04, I − Ks = 2.97 ± 0.05) and CFHT-BL−38 (I = 19.01 ± 0.04, I − Ks = 3.12 ± 0.05), defining the color/magnitude range in which the LDB is located. We contend that the LDB for Blanco 1 is located at I = 18.78 ± 0.24 and I − Ks = 3.05 ± 0.10, as represented by the box in the inset of Figure 1.

3.3. LDB Age of Blanco 1

Having identified the color/magnitude of Blanco 1’s LDB, we can now determine its age using the predicted Li-depletion rates from current PMS evolutionary models, specifically the models from Chabrier & Baraffe (1997) and Baraffe et al. (1998, hereafter BCAH98). Here, we assume the LDB is located at the luminosity where 99% of the Li is predicted to be depleted in a star. The high sensitivity of the rate of Li depletion to stellar
mass (or luminosity) means assuming the LDB is instead located at 90% depletion would change the measured LDB age by only ±1 Myr (see Jeffries & Oliveira 2005).

We calculate \( M_I = 12.17 \) and \( (I - K_s)_0 = 3.02 \) for the LDB of Blanco 1 using an intrinsic distance modulus from HIPPARCOS (6.58 ± 0.12, van Leeuwen 2000), and adopt \( E(I - K_s) = 0.02 \) and \( A_I = 0.03 \) (average of published coefficients; see Cargile et al. 2009). Converting intrinsic LDB colors/magnitudes to the bolometric luminosity necessary for comparison to predictions from PMS models, we use two different bolometric corrections (BCs). First, we use an empirical \( I/I - K_s \) to BC relationship given by Leggett et al. (1996). Second, we employ the BC and color–\( T_{eff} \) relationships calculated by BCAH98 using DUSTY non-gray model atmospheres (Baraffe et al. 2002). In order to accurately compare the BCAH98 models to our observations, we convert their predicted CIT K photometry to the 2MASS \( K_s \) using the relationship in Carpenter (2001). Listed in Table 2 are the physical parameters predicted by BCAH98 models for our measured \( M_I/I - K_s \) location of Blanco 1’s LDB with its respective uncertainty. We calculate a LDB age of 132 ± 24 Myr using the empirical BC, and a slightly younger age, 124 ± 18 Myr, using the BC from BCAH98 + DUSTY; however within their errors, both ages are in agreement.

The uncertainties we place on the LDB ages for Blanco 1 are derived solely from observational errors in the LDB’s \( M_I \) and intrinsic \( I - K_s \) values: the error in the distance modulus (0.1 mag), the photometric uncertainty in the objects (\( \sigma_I = 0.04 \) mag, \( \sigma_{I - K_s} = 0.05 \) mag), and, most significantly, the error in the LDB location in the \( I/I - K_s \) CMD. The precision of the LDB’s location is defined by the color/magnitude difference between CFHT-BL-24 and CFHT-BL-38, as illustrated by the box in the inset of Figure 1; \( \sigma_{I,LDB} = 0.24 \) mag, \( \sigma_{I - K_s, LDB} = 0.10 \) mag.

4. DISCUSSION AND IMPLICATIONS

Upper main-sequence (UMS) isochrone ages derived using high-mass stellar evolutionary models that do not include convective-core overshooting are seen to be systematically ∼1.5 times younger than LDB ages (e.g., Barrado y Navascués et al. 2004). Convective-core overshoot has the effect of mixing more hydrogen into stellar cores, hence prolonging stellar main-sequence lifetimes. Therefore, increasing the amount of core overshoot can thereby bring into agreement measured UMS and LDB ages.

Of the seven open clusters with identified LDBs, including our new identification in Blanco 1, four (IC 4665, (Cargile & James 2010); NGC 2547, (Naylor & Jeffries 2006); Pleiades, (Naylor 2009); Blanco 1, (D. J. James et al. 2011, in preparation)) also have UMS ages measured using the recently developed \( r^2 \)-fitting technique and the Geneva stellar evolutionary models. The black dashed line represents equality between the two age determination methods and is not a fit to the data.

(A color version of this figure is available in the online journal.)

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