AN IMPROVED DETERMINATION OF THE LITHIUM DEPLETION BOUNDARY AGE OF BLANCO 1 AND A FIRST LOOK ON THE EFFECTS OF MAGNETIC ACTIVITY

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ABSTRACT

The lithium depletion boundary (LDB) is a robust method for accurately determining the ages of young clusters, but most pre-main-sequence models used to derive LDB ages do not include the effects of magnetic activity on stellar properties. In light of this, we present results from our spectroscopic study of the very-low-mass members of the southern open cluster Blanco 1 using the Gemini-North Telescope, program IDs: GN-2009B-Q-53 and GN-2010B-Q-96. We obtained Gemini Multi-Object Spectrograph spectra at intermediate resolution for cluster candidate members with \( I \approx 13-20 \) mag. From our sample of 43 spectra, we find 14 probable cluster members by considering proximity to the cluster sequence in an \( I/I-K_s \) color–magnitude diagram, agreement with the cluster’s systemic radial velocity, and magnetic activity as a youth indicator. We systematically analyze the \( \text{H}_\alpha \) and \( \text{Li} \) features and update the LDB age of Blanco 1 to be \( 126^{+14}_{-13} \) Myr. Our new LDB age for Blanco 1 shows remarkable coevality with the benchmark Pleiades open cluster. Using available empirical activity corrections, we investigate the effects of magnetic activity on the LDB age of Blanco 1. Accounting for activity, we infer a corrected LDB age of \( 114^{+9}_{-10} \) Myr. This work demonstrates the importance of accounting for magnetic activity on LDB inferred stellar ages, suggesting the need to reinvestigate previous LDB age determinations.

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

Online-only material: color figures

1. INTRODUCTION

As low-mass stars (\(<1M_\odot\)) contract along the pre-main-sequence (PMS), their internal temperature rises. When the temperature of the stellar interior reaches \( \sim 2.5 \times 10^6 \) K, lithium is destroyed by \( ^7\text{Li}(p, \alpha)^4\text{He} \) and \( ^7\text{Li}(p, \alpha)^4\text{He} \) proton capture reactions (e.g., Bodenheimer 1965). The elapsed time to reach Li-burning temperatures is a sensitive function of mass and thus depends very sensitively on the luminosity (Bildsten et al. 1997; Ushomirsky et al. 1998). PMS low-mass stars are fully convective, thus the mixing timescale is short and, since the temperature dependence of the nuclear reactions is steep, these stars rapidly deplete their Li content. For coeval stellar groups, like open clusters or moving groups, the determination of the luminosity at which stars transition from exhibiting Li in their atmospheres to being fully depleted provides a very precise age estimate. Moreover, the lithium depletion boundary (LDB) technique is relatively model-insensitive, rendering similar ages to within \( \pm 10\% \) (Burke et al. 2004), making it a highly robust method which can lead to the identification of missing input physics when compared with other age-dating methods. The LDB method originated with Basri et al. (1996) who first applied it to the Pleiades cluster, leading to the discovery of the first brown dwarf using the lithium test.

Ages of open clusters are traditionally determined by matching their Hertzsprung–Russell diagrams to distance-dependent, theoretical stellar isochrones. In particular, stars in and near the region close to the main-sequence turn-off (MSTO) are the most sensitive determinants of the age because they are evolving quickly. MSTO fitting can be improved in precision through statistical techniques that take account of the usually small number of stars at the turn-off, but the method remains limited by several factors. For very young clusters (<100 Myr), the MSTO corresponds to the minimum number of objects for their initial mass function, and unresolved, undetected binary/multiple systems can significantly affect MSTO ages. At the same time, derived ages are highly dependent on the input models used and the physical constraints bounding them. One major influence, for example, has been the inclusion of core mixing in intermediate-mass stars that led to ages being systematically increased by \( \sim 50\% \) for clusters with ages less than 1–2 Gyr (Maeder 1974; Naylor 2009). The LDB method offers a means to critically test the MSTO technique and it has several advantages. First, the physical processes involved in MSTO and LDB stars are completely different and thus are independent. Second, the fundamental physics underpinning the LDB method is much more simple and straightforward to compute and calibrate than for hot, high-mass stars because stars lying close to the LDB point in young clusters are fully convective. While the exteriors of very-low-mass stars (<0.2 \( M_\odot \)) may host complex magnetic activity phenomena that are challenging to understand, their interiors are fairly straightforward. Third, the nature of open cluster mass functions implies that there are many more stars that can be exploited to establish the LDB than there are at the MSTO (Soderblom 2010; Soderblom et al. 2013). However, one may obtain a relatively sparse data set due to efforts of removing field star contaminants.

The LDB method has limitations in its applicability. It can only be applied to very young clusters because of the rapidity of Li depletion. Furthermore, very-low-mass stars at the LDB are extremely faint, thus only very nearby clusters are amenable to observation, usually by 8–10 m class telescopes. Such stars are typically mid-M-dwarfs in the cluster, and for physical and practical reasons, the LDB method is limited in its utility for...
ages in the range $20 < \tau < 200$ Myr. Currently, seven other open clusters and two moving group associations have LDB age determinations, but only the Pleiades is similar in age (125 ± 8 Myr; Stauffer et al. 1998, 126 ± 11 Myr; Burke et al. 2004, gyrochronology age of 134$^{+9}_{-7}$ Myr; Cargile et al. 2014) to Blanco 1. As yet, no open cluster with an isochrone age $>130$ Myr has been investigated using the LDB method.

Blanco 1 is an open cluster whose near-solar composition, [Fe/H] $= +0.04 \pm 0.04$ (Ford et al. 2005), and age similarity to the Pleiades make it ideal for direct comparison and systematic characterization of age diagnostics. Previous age estimates for Blanco 1 suggest that it is a relatively young open cluster (100–150 Myr; Panagi & O’Dell 1997; Moraux et al. 2007). Blanco 1 is also considered nearby at a modest distance of 207 pc (van Leeuwen 2009), and lies at high Galactic latitude ($b = -79^\circ$). Initially, a subset of low-mass Blanco 1 candidates were analyzed, and the LDB age was determined to be 132 ± 24 Myr (Cargile et al. 2010). In this manuscript, we present additional Gemini-North spectra of Blanco 1 LDB candidates, and describe a consistent analysis for the full sample of Blanco 1 spectroscopic observations, which allows us to further resolve the LDB location and derive a more precise LDB age for the cluster.

Despite the similarity of derived LDB ages among different PMS models, most models do not account for physical processes in an inclusive and realistic stellar environment, such as rotation and magnetism prevalent in low-mass star PMS evolution. Such omission may produce a range of inaccurate stellar parameters, particularly the radius ($R$) and effective temperature ($T_{\text{eff}}$) of a star (Morales et al. 2008). One additional goal of this project is to quantify the extent that activity influences these stellar parameters, allowing us to correct for the age determinations based on the LDB technique. Using empirical relationships presented in Stassun et al. (2012), we will account for the magnetic activity by effectively determining the properties of inactive Blanco 1 stars. In doing so, we enable a consistent LDB age determination from standard PMS models.

In Section 2, we describe the data arising from our new medium-resolution spectroscopic campaign of additional Blanco 1 low-mass candidate members. In Section 3, we present our analysis, emphasizing the H$\alpha$ and Li$\text{i}$ features, which are important to the astrophysical interpretations for inferring the LDB age of Blanco 1. In Section 4, we present the details of a clear methodology for establishing LDB boundaries as well as the derivation of the LDB age for our sample; we then present the empirical corrections for magnetic activity and derive a new LDB age based on the changes found in $T_{\text{eff}}$ and $R$ for the stars which define the LDB boundaries. We conclude the manuscript with a summary of our work in Section 5.

2. TARGETS, OBSERVATIONS, AND DATA REDUCTION

A photometric catalog of the very-low-mass members of Blanco 1 was compiled by Moraux et al. (2007), where they selected cluster candidates on the basis of their location in color–magnitude diagrams (CMDs) compared to theoretical isochrones (100 and 150 Myr). Furthermore, Moraux et al. took low-resolution optical spectra for 17 of the brightest brown dwarf candidates and found H$\alpha$ in emission for 5 of them, which is an initial indicator of youth. Their list of 15 probable members straddling the substellar boundary provides us with an ideal sample for investigating the LDB of Blanco 1. These probable low-mass cluster members have $I \approx 18–20$, corresponding to the expected luminosity of Blanco 1 LDB, which in a cluster of age $\sim 100$ Myr at a distance of $\sim 200$ pc should be $I \approx 19$ (Burke et al. 2004; Cargile et al. 2010).

For a subset of these objects, Cargile et al. (2010) have previously presented medium-resolution spectra of the Li$\text{i}$ ($6707.8$ Å) region. In this work, we have obtained additional spectra using the same instrument and setup as were employed for the Cargile et al. study. Both the previous and new spectra were obtained with the Gemini Multi-Object Spectrograph (GMOS) in queue schedule mode on the Gemini-North Telescope (Hook et al. 2004), under program IDs GN-2009B-Q-53 and GN-2010B-Q-96. We used 1′′ slit sizes to yield a 2 pixel resolving power of $\sim 4400$ over a spectral wavelength range of 5700–8000 Å and dispersion of 0.67 Å per pixel.

Moreover, a recent optical survey performed using the SMARTS 1.0 m telescope at CTIO provided additional candidates with $I \approx 13.0–17.5$; these targets were identified as photometric candidate members from their location near to the cluster sequence in an optical CMD (D. J. James et al. in preparation). Altogether, our sample contains 43 spectra (13 targets selected from Moraux et al. 2007, 30 from the SMARTS survey), from which we find 14 high confidence members of the Blanco 1 cluster. In addition, we retain spectra of the radial velocity (RV) standard star GJ 905 (M6) from our initial GN-2009B-Q-53 program, which was observed and analyzed in an identical manner to the Blanco 1 candidates.

All of our GMOS spectra are reduced using standard reduction routines in the IRAF5 Gemini-GMOS package, including bias removal, flat-fielding, aperture extraction, and wavelength calibration. Our spectral signal-to-noise ratios (S/Ns) per pixel ranged from approximately 10 to 500 for the faintest and brightest targets, respectively. RVs for each Blanco 1 target were measured using the fxcor procedure in IRAF by cross-correlating target GMOS spectra with the RV standard star, GJ 905. We performed cross-correlation in the wavelength region $\sim 6600–7000$ Å, masking out regions rich in telluric features. Uncertainties on these RVs can be relatively large (up to $\sim 15$ km s$^{-1}$), which is primarily due to the low S/N of the target spectra and the medium resolution of our observations.

3. ANALYSIS

We developed a spectral analysis code in Python to completely automate the analysis method in order to consistently derive equivalent widths (EWs) and spectral indices. The spectral type of the object is determined via TiO and CaH spectral indices, whose methodology we describe in Section 3.1. EWs of the H$\alpha$ (6562.8 Å) and Li$\text{i}$ (6707.8 Å) spectral features are measured systematically, using established wavelength regions flanking both features to carry out the linear normalization procedure to the pseudo-continuum. The systematic EW measurement and error estimation for the H$\alpha$ line are discussed in Section 3.2. Cluster membership criteria are laid out in Section 3.3, where we identify high confidence cluster members. In Section 3.4, we describe the measurement of the Li$\text{i}$ feature, which we then place in the context of the curve of growth to derive lithium abundance, $\alpha$(Li$\text{i}$), in Section 3.4.3, allowing us to provide insight as to the stage of Li depletion for our targets. In Section 4.2.2, we describe how we obtain log $L_{\text{H}\alpha}/L_{\text{bol}}$ values,

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5 IRAF 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.
which are used to account for magnetic activity and determine their concomitant changes in $R$ and $T_{\text{eff}}$. Observational and empirical data for the cluster members are summarized in Table 1, which include positions, photometric properties, spectral types, RVs, EW (Hα), and EW (Li) for each object. We include $1\sigma$ errors for both the Hα and Li I EW measurements for completeness, with $3\sigma$ upper limits reported for Li non-detections.

### 3.1. Spectral Indices

Spectral types are estimated from the value of the TiO (7140 Å) and CaH (6975 Å) narrow-band spectral indices. They are defined as

\[
\text{TiO}(7140\,\text{Å}) = \frac{C(7020 - 7050\,\text{Å})}{\text{TiO}(7125 - 7155\,\text{Å})}
\]

\[
\text{CaH}(6975\,\text{Å}) = \frac{C(7020 - 7050\,\text{Å})}{\text{CaH}(6960 - 6990\,\text{Å})},
\]

where C (7020–7050 Å) represents the pseudo-continuum, and TiO (7125–7155 Å) and CaH (6960–6990 Å) represent the molecular absorption bands, integrated in the indicated wavelength intervals (Briceno et al. 1998; Oliveira et al. 2003). The CaH index is sensitive to gravity and helps us verify that the objects we observed are, in fact, dwarfs. However, these narrow-band indices are not, by themselves, good indicators of cluster membership since the sample is sure to be contaminated with other foreground field M-dwarfs with similar index values (Jeffries et al. 2004). The spectral type of each target is estimated from the relationship between TiO (7140 Å) index and spectral type calibrated from standards in Montes et al. (1997) and Barrado y Navascues et al. (1999; see Table 6 in Jeffries et al. 2013). The resulting spectral types are reported in Table 1. We adopt a typical uncertainty of half a spectral subclass (Oliveira et al. 2003; Jeffries & Oliveira 2005).

The CaH versus TiO spectral indices for the Blanco 1 candidates. The spectral type for a given object is determined with the TiO index, while the CaH index can be used to eliminate background giant stars from the sample. Note the transition of the Hα feature from absorption to zero emission as one tends to a higher CaH–TiO index (or later M spectral types). The solid line represents the locus of approximate positions for giant stars in CaH vs. TiO space (Allen & Strom 1995).

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

### Table 1

Blanco 1 Members Ordered by Intrinsic I Magnitude

| Star Name | R.A. | Decl. | $I_0$ | $(I - K_s)$ | SpT | RV | EW(Hα) | log $L_{\text{bol}}/L_{\odot}$ | EW(Li) | At(Li) |
|-----------|------|-------|-------|-------------|-----|-----|--------|-------------------------------|--------|--------|
| B1opt-6335 | 00:00:00.0 | 00:28:38.68 | -30:08:30.01 | 13.156 ± 0.011 | 1.724 ± 0.024 | K5.5 | -10 ± 8 | -2.39 ± 0.06 | -3.6759 | 0.087 ± 0.087 |
| B1opt-18229 | 00:01:39.76 | 00:04:38.24 | 13.315 ± 0.016 | 1.703 ± 0.029 | K5.3 | 15 ± 12 | 1.19 ± 0.12 | 3.6969 | <0.249 | <1.348 |
| B1opt-2156 | 00:07:40.79 | 00:05:56.58 | 14.45 ± 0.030 | 2.09 ± 0.042 | M0.4 | 7 ± 6 | 3.88 ± 0.06 | 3.6883 | <0.177 | <1.593 |
| B1opt-13328 | 00:04:22.73 | 00:23:06.00 | 15.86 ± 0.001 | 2.27 ± 0.051 | M3.8 | 1 ± 5 | 17.89 ± 0.04 | 3.5062 | <0.054 | <0.698 |
| CFHT-BL-16 | 00:01:28.38 | 00:06:09.15 | 18.30 | 2.85 | M5.1 | 4 ± 6 | -4.50 ± 0.14 | 4.1908 | <0.357 | <1.727 |
| CFHT-BL-22 | 00:00:02.62 | 00:20:15.90 | 18.47 | 2.90 | M5.6 | 24 ± 5 | -6.22 ± 0.07 | 4.0863 | 0.320 ± 0.137 |
| CFHT-BL-24 | 00:07:50.53 | 00:05:09.46 | 18.51 | 2.95 | M5.6 | 3 ± 8 | 4.67 ± 0.13 | 4.1053 | <0.291 | <1.374 |
| CFHT-BL-25 | 00:00:02.84 | 00:17:43.98 | 18.62 | 3.06 | M5.6 | 28 ± 6 | -6.26 ± 0.16 | 4.1991 | <0.294 | <1.313 |
| CFHT-BL-29 | 00:00:17.35 | 00:46:20.32 | 18.77 | 3.03 | M6.2 | 29 ± 7 | 5 ± 15 | 2426.68 | <0.333 | <1.490 |
| CFHT-BL-38 | 00:05:13.07 | 00:27:35.78 | 18.98 | 3.10 | M6.4 | 7 ± 11 | 5 ± 11 | 1500.00 | <0.577 | <2.790 |
| CFHT-BL-43 | 00:04:32.84 | 00:18:41.40 | 19.02 | 3.13 | M6.3 | 7 ± 10 | 5 ± 10 | 1400.00 | <0.577 | <2.790 |
| CFHT-BL-46 | 00:00:28.38 | 00:06:41.94 | 19.06 | 3.37 | M6.0 | 4 ± 7 | 5 ± 10 | 1400.00 | <0.577 | <2.790 |
| CFHT-BL-45 | 00:01:35.61 | 00:03:09.90 | 19.23 | 3.27 | M6.2 | 25 ± 12 | 4 ± 12 | 1500.00 | <0.577 | <2.790 |
| CFHT-BL-49 | 00:04:28:38 | 00:20:37.00 | 19.46 | 3.56 | M6.3 | 3 ± 18 | -2.42 ± 0.66 | 4.9226 | 1.930 ± 0.120 |

Notes.

- Targets are from the B1opt–SMARTS optical survey (D. J. James et al. in preparation) and CFHT-BL: Moraux et al. (2007). In this paper, targets will be referenced by the identification number written in bold.
- J2000.0 coordinates.
- The $K_s$ values come from the Two Micron All Sky Survey (2MASS) catalog for stars with $I < 17.5$, or from Moraux et al. for $I > 17.5$. For $I > 17.5$, which is relevant to the region of the LDB, the photometric uncertainty is estimated as $\sigma_{K_s} = 0.03, \sigma_I = 0.04, \sigma_{I-K_s} = 0.05$.
- Spectral types are good to within half a subclass.
- Negative values indicate that the line is in emission.
- The systematic uncertainty for log $L_{\text{bol}}/L_{\odot}$ is about 0.5 dex.
- Members with Li report EW(Li) from our MCMC analysis, while 3σ upper limits come from Equation (1).
non-members because at the age of Blanco 1, we expect such low-mass bona fide cluster members to be chromospherically active. In addition, zero-Hα stars can be very active stars with strong chromospheres as the Hα core may be filled in by active region emission (Panagi & O’dell 1997); hence, such objects may be young cluster members as well. We return to Hα as a membership criterion in Section 3.3.

3.2. The Hα Feature

As well as establishing cluster membership, Hα EW can be employed in empirical corrections for magnetic activity (discussed in Section 4). Our method of obtaining Hα EW consistently is achieved by performing continuum normalization with a 10 Å span of wavelength neighboring the Hα feature. We use the intervals 6545–6555 Å and 6570–6580 Å and find no significant issues with other spectral features within these intervals. The mean is calculated from each 10 Å segment, and the line connecting both mean values establishes the continuum level. The Hα EW is then determined by measuring excess from the normalized continuum using a Gaussian line profile, which is obtained from a minimized least-squares fit. A simple interpolation is performed at the boundaries of the Hα feature so that the baseline will exactly measure flux above unity (for emission) or below unity (for absorption). Figure 2 demonstrates such an EW measurement process for star 22. EW uncertainties are estimated from

$$\sigma_{\text{EW}} \simeq 1.5 \times \frac{\text{FWHM} \times \text{S/N}}{\rho},$$

where FWHM, ρ, and S/N are the full width half maximum of the Gaussian fit, the pixel dispersion scale in Å, and the signal-to-noise ratio, respectively (Cayrel 1988).

3.3. Membership Selection

The stars from our GMOS sample can be classified as Blanco 1 cluster members upon consideration of three different membership criteria: (1) that the photometry of a candidate member is consistent with the cluster sequence in an $I/I_s - K_s$ CMD; (2) its 3σ RV must be within the range of +2 to +10 km s$^{-1}$; (3) the Hα line EW must be in emission or zero and comparable to similar-mass stars in the Pleiades cluster.
et al. 1998). These clusters share a similar age, and a given EW (Hα) is expected to be comparable to similar-mass stars among these populations. Our sample of low-mass members of Blanco 1 exhibits very active chromospheres at mid-M spectral types. This appears to be comparable to the low-mass activity found in the Pleiades. Recorded in Table 1 are our measurements of EW (Hα) for high confidence Blanco 1 members. Our measurements and other observational data for objects determined to be cluster non-members are reported in the Appendix.

3.4. Lithium

3.4.1. EW Measurement Via Spectral Subtraction

A spectral subtraction technique is carried out in our study by using a catalog of M-dwarf templates 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 M0–L0. In particular, we use the catalog of inactive spectra for spectral types M0–M7, where the measured EW of the Hα feature was <1 Å in emission. Moreover, since the majority of the combined spectra used for these templates are field M-dwarfs, they are expected to be old enough (∼Gyr) to have destroyed their initial lithium. Due to the lack of K-type templates, we must compare the K-type stars with the M0 SDSS template. Otherwise, we paired a given GMOS spectrum with a template by rounding to the nearest spectral type determined from the TiO spectral index described in Section 3.1.

In the determination of the Li EW, the spectrum of the target is shifted to the rest frame, normalized, smoothed, and compared with an SDSS template spectrum. Both the target and template are normalized by using small wavelength spans (specifically 6703–6706 Å and 6710–6712 Å). Data were smoothed with a Gaussian kernel, and the template is convolved to match the resolution of our GMOS spectrum. EWs are measured in the residual spectrum over an interval of ∼4 Å centered on Li. Figure 6 shows an example of measuring the Li EW for star 22 (M5.6) and 6335 (K5.5), confirming detectable lithium in these objects for the first time. Present in some of our spectra with low S/N are telluric sky absorption lines near Si that could not be removed because of poor sky-subtraction. The error quoted for EW (Li) in Figure 6 is estimated using Equation (1).

In Figure 7, we show the six low-mass Blanco 1 members that contain detectable Li. Telluric Si features are indicated. It is evident that as one goes fainter, the signal in Li becomes more significant. On the other hand, the S/N diminishes, increasing the difficulty to match the continuum. Targets 38, 43, 45, and 49 were reported to have Li detected >3σ in Cargile et al. (2010), although EW measurements at the time were not possible. Now, we have identified two additional members (targets 22 and 6335). In Section 4, we explain how target 22 in particular influences the location of the LDB.

3.4.2. EW Measurement Via MCMC

Due to the low S/N of the spectrum around the Li I line (typically ∼10 for the faintest Blanco 1 stars), we sought to provide a robust characterization of our Li EW measurements. Here, we incorporate an affine-invariant MCMC to sample the...
posterior probability distribution functions for our Li I EWs using the emcee package developed by Foreman-Mackey et al. (2013). After we subtract the appropriate template for each target spectrum, we model the resulting residual with a Gaussian as a likelihood function, and calculate 80,000 samples (400 MCMC “walkers” × 200 iteration steps) of the posterior probability distribution. We place an uninformative prior on the amplitude of our Gaussian model, constraining it to only consider Li in absorption, as well as normal priors on the Gaussian σ and centroid based on a priori knowledge of the GMOS instrument resolution and predicted 6707.8 Å Li line center, respectively. For each star, we set a conservative estimate of the variance in our flux measurement based on a S/N = 10.

We show in Figure 8 examples of the marginalized posterior distributions for a Gaussian model of the Li absorption line, as well as an inferred EW distribution based on the predicted cumulative function. The Li EWs we report in Table 1 are determined from the mode of the marginalized distribution with uncertainties based on the inter-68th percentile range (1σ errors).

In Figure 9, we display the distribution of EW (Li) for our modeling of Blanco 1 cluster members. A clear pattern is apparent in these data; namely, we detect little or no Li in earlier spectral types (≤M6), but measure significant Li absorption in the latest spectral type stars in Blanco 1. In Section 4, we further investigate the quantitative nature of this distribution in the context of predictions from PMS Li models. However, the overall spectral type dependent transition in the EW (Li) of Blanco 1 stars is qualitatively consistent with the identification of the LDB in the cluster.

3.4.3. Lithium Abundance

In order to calculate Li abundances, it is necessary to convert intrinsic color to $T_{\text{eff}}$. For the stars in our spectroscopic survey, we used BT-Settl models (Allard et al. 2011) to obtain $T_{\text{eff}}$. Jeffries & James (1999) performed a lithium study on G- and K-dwarf members of Blanco 1, but we use the empirical relationship given in Casagrande et al. (2010) to derive $T_{\text{eff}}$ for these stars. Abundances were calculated from EW (Li) using an appropriate curve of growth for the Li I (6707.8 Å) feature; for hotter stars ($T_{\text{eff}} > 4000$ K), we used the calculations given in Soderblom et al. (1993), and for cooler objects, we used the models presented in Pavlenko et al. (1995) and Pavlenko & Maguzzo (1996). We note that our procedure of measuring EW (Li) after subtracting a template spectrum has the effect of mitigating the contribution of the nearby contaminating Fe line at 6707 Å, as well as the large molecular TiO absorption that is present in the Li region. Non-LTE corrections for

![Figure 7](image-url)  
Figure 7. Blanco 1 low-mass members exhibiting Li I absorption (gray dashed line). Each Blanco 1 GMOS spectrum is indicated along with its template (solid black and gray lines, respectively) and intrinsic I magnitude.

![Figure 8](image-url)  
Figure 8. Posterior probability distributions for the Gaussian parameters for our modeling of targets 22 and 6335. Best-fit values for the parameters are based on the mode of the distributions (red line) and formal 68th percentile uncertainty ranges are indicated with shaded regions.

(A color version of this figure is available in the online journal.)
Li abundances presented in Carlsson et al. (1994) were applied to the hotter Blanco 1 stars. For the cooler stars, we did not correct the abundances for non-LTE effects as these are negligible at cool temperatures (Pavlenko et al. 1995; Zapatero Osorio et al. 2002). We adopt an initial Li abundance of $\log N_0(\text{Li}) = 3.1$ for the cluster (Zapatero Osorio et al. 2002).

Figure 10 shows the distribution of Li abundance for Blanco 1 versus absolute $I$ magnitude, $M_I$. Here, the three regimes of Li depletion are present: (1) stars more massive than 0.6 $M_\odot$ gain radiative interiors and only lose a small amount of Li depletion (green squares); Jeffries & James (1999); (2) stars in the “Li chasm” (Basri 1997) that have fully depleted their initial Li supply ($7 \lesssim M_I \lesssim 11$); and (3) low-mass stars that still exhibit Li content ($M_I \gtrsim 12$). It is evident that for hotter stars ($M_I < 6$), with the exception of a few points, the models fail to reproduce the overall observed abundance distribution in the cluster. The Li detections near the substellar boundary ($M_I \approx 12$) suggest that target 22 is currently depleting Li, while the fainter Li detections lie near full natal Li abundance.

4. RESULTS

4.1. Locating the LDB

In the identification of the LDB for this study, we establish a set of rules to demarcate the boundaries of the LDB. First, having identified the cluster members, we concentrate on the targets that contain lithium. Based on the insight we have gained from the lithium abundance of Blanco 1 members, the LDB boundaries are set in the following way: the target currently depleting lithium (star 22) establishes the bright blue (upper left) corner; the nearest target in the CMD with full lithium content (star 38) establishes the faint red (lower right) corner. The edges of the LDB box incorporate the photometric uncertainties in the stars defining these corners (stars 22 and 38): $\sigma_{I-K_s} = 0.03$, $\sigma_I = 0.04$, $\sigma_{I-K} = 0.05$. We define the center of this box to be the location of the LDB in Blanco 1, the brightest luminosity at which Li content still remains unburned in the atmospheres of low-mass stars.

Figure 11 shows the CMD for intrinsic $I$-band magnitude versus $I - K_s$ for the stars in our sample that have Li detections among the Blanco 1 low-mass members. The Li detection at $I_0 \approx 13$ is from a K-dwarf in the cluster. This star formed a radiative core early enough in its PMS evolution to stop convection down to the stellar depth necessary to burn Li, and thus still retains some of its Li content. We also illustrate in Figure 11 our definition of the LDB region as the shaded box.

4.2. LDB Ages for Blanco 1

4.2.1. Standard LDB Age

Previously in Cargile et al. (2010), with a limited data set, the authors provided a preliminary identification of the LDB in Blanco 1 and found it to be located at $I = 18.78 \pm 0.24$ and $I - K_s = 3.05 \pm 0.10$. They calculated the absolute $I$ magnitude, $M_I$, of the LDB using the distance modulus from
Table 2
LDB Parameters for Blanco 1

|                |  \( I_0 \) Versus \( (I - K_{s,0}) \) (Standard) |  \( I_0 \) Versus \( (I - K_{s,0}) \) (Corrected) |  \( K_{s,0} \) Versus \( (I - K_{s,0}) \) (Standard) |  \( K_{s,0} \) Versus \( (I - K_{s,0}) \) (Corrected) |
|----------------|-----------------------------------------------|-----------------------------------------------|-----------------------------------------------|-----------------------------------------------|
| Location       | \( (I - K_{s,0}) = 2.950 \pm 0.100 \)         | \( (I - K_{s,0}) = 2.765 \pm 0.120 \)         | \( (I - K_{s,0}) = 2.950 \pm 0.100 \)         | \( (I - K_{s,0}) = 2.765 \pm 0.120 \)         |
|  \( M_{I_s} \)  | \(-12.11_{-0.28}^{+0.26} \)                   | \(-12.28_{-0.28}^{+0.27} \)                   | \(-12.49_{-0.28}^{+0.28} \)                   | \(-12.49_{-0.29}^{+0.29} \)                   |
| Age (Myr)      |                                              |                                              |                                              |                                              |
| BCAH           | 126\(_{+13}^{-14}\)                           | 124\(_{+14}^{-13}\)                           | 145\(_{+15}^{-14}\)                           | 141\(_{+15}^{-14}\)                           |
| P&M            | 152\(_{+24}^{-23}\)                           | 124\(_{+14}^{-13}\)                           | 
| \( \log(L) / L_{\odot} \) |                                              |                                              |                                              |                                              |
| BCAH           | \(-2.910_{-0.062}^{+0.060} \)                | \(-2.818_{-0.077}^{+0.075} \)                | \(-2.893_{-0.066}^{+0.069} \)                | \(-2.893_{-0.066}^{+0.069} \)                |
| P&M            | \(-3.026_{-0.108}^{+0.120} \)                | 

Notes.

a Absolute magnitudes are calculated using the Hipparcos distance modulus of 6.58 mag. The first and second sets of uncertainties are when using DUSTY synthetic photometry and the empirical bolometric corrections of P&M, respectively. These errors include the uncertainty in the photometry, error in the distance modulus, and error in the bolometric correction for P&M. LDB parameters are not available for the \( K_{s}/I - K_{s} \) LDB locations using the P&M bolometric corrections.

b Refers to BCAH models and synthetic photometry from DUSTY model atmospheres (Baraffe et al. 2002).

c Refers to the use of empirical bolometric corrections from Pecaut & Mamajek (2013) to directly determine luminosity.

**Hipparchos (6.58 ± 0.12; van Leeuwen 2009)** and corrected for reddening and extinction by adopting \( E(I - K_s) = 0.02 \) and \( A_I = 0.03 \). Using predicted Li-depletion rates from PMS models, specifically Chabrier & Baraffe (1997) and Baraffe et al. (1998, hereafter BCAH), Cargile et al. used the luminosity at which 99% of the star’s natal Li is destroyed to measure the LDB age for Blanco 1 to be 132 ± 24 Myr. We designate their method as the “standard” LDB age determination technique.

Here, we determine the standard LDB age using a similar approach to Cargile et al. Using our stars 22 and 38 to establish the LDB boundaries, the updated Blanco 1 LDB is located at \( I_0 = 18.69 \pm 0.26 \) and \( (I - K_{s,0}) = 2.95 \pm 0.10 \). We determine \( M_{I_s} \) using the same distance modulus from Hipparcos, as well as extinction and reddening corrections used in Cargile et al. We first calculate the LDB age of Blanco 1 using the BCAH models and synthetic photometry from the DUSTY model atmospheres (Baraffe et al. 2002). Alternatively, we also calculate the LDB age using the empirical bolometric corrections from Pecaut & Mamajek (2013, hereafter P&M) to derive luminosity directly from our absolute \( I \) magnitudes. In Table 2, we list our measured LDB parameters for Blanco 1 using the BCAH PMS models with both synthetic photometry and using empirical corrections from P&M.

For clarity, Figure 12 shows the region of the \( I/I - K_s \) CMD near the LDB of Blanco 1. As in Figure 11, the LDB is established by the Li detections in targets 22 and 38. Using the “standard” LDB technique, the BCAH PMS models with synthetic photometry, and our new Li detections, the LDB in Blanco 1 is found at a \( \log(L) = -2.910 \, L_{\odot} \), resulting in an updated LDB age of 126\(_{+12}^{-13}\) Myr. We have included a 126 Myr BCAH LDB luminosity locus in Figure 12 to illustrate this age measurement, which is strikingly similar to the age of the Pleiades (126 ± 11 Myr; Burke et al. 2004).

One might instead consider that the position of the LDB could be defined entirely by target 22, given that this object evidently lies within the Li depletion zone (see Figure 10). For stars at full natal Li abundance, \( A(Li) = 3.1 \), thus the LDB (defined at 99% depletion) is found when \( A(Li) = 1.1 \). Conceivably, the absolute \( I \) magnitude range for the LDB would be bounded by the abundance errors for star 22. We interpolate over the abundance isochrones to calculate \( M_{I_s} \) for \( A(Li) = 0.821, 1.1, \) and 1.974 dex, which correspond with the error bounds of star 22 and the 99% Li depletion level. The 110 Myr model isochrone matches well with the data, and we find at \( A(Li) = 1.1 \) that \( dM_{I_s} / dA(Li) = 0.214 \, \text{mag} \, \text{dex}^{-1} \). Thus, the LDB using this interpretation is \( I_0 = 18.45^{+0.19}_{-0.10} \) mag, and the corresponding LDB age is 114 ± 7 Myr. While this abundance-derived age is in statistical agreement with our standard LDB age, the reported error (6.1%) is smaller than the 10% systematic error found for the uncertainties associated with the stellar evolution models and bolometric corrections (Burke et al. 2004). Therefore, we prefer the more conservative approach described above since our method results in the observed precision of the LDB age that is no better than the predicted accuracy of the LDB technique at ~120 Myr.
4.2.2. Activity-corrected LDB Age

Investigations have found that the fundamental properties of low-mass stars can be altered in the presence of strong magnetic activity (López-Morales 2007; Ribas 2006). Morales et al. (2008) have provided observational evidence that active stars are cooler than inactive stars of similar luminosity, therefore, implying that active stars have a larger radius. Their results generalize for all active low-mass stars—single or binary. In the context of the LDB, we thus expect that active stars would be more massive than initially thought, and their associated ages would be younger.

Stassun et al. (2012) provide empirical relations to determine the amount by which the effective temperatures ($T_{\text{eff}}$) and radii ($R$) of low-mass stars and brown dwarfs are altered due to chromospheric activity. Their results presented a strong correlation between the strength of Hα emission in active M-dwarfs, and the degree to which their temperatures are suppressed and radii inflated compared to inactive stars. In order to determine the change in $T_{\text{eff}}$ and $R$ as a result of stellar activity, the following empirical relations were implemented:

\[
\Delta T_{\text{eff}}/T_{\text{eff}} = m_T \times (\log L_{\text{Lbol}}/L_{\text{bol}} + 4) + b_T,
\]

\[
\Delta R/R = m_R \times (\log L_{\text{Lbol}}/L_{\text{bol}} + 4) + b_R,
\]

where $m$ and $b$ are linear coefficients. The averaged values, as defined in Stassun et al. (2012), are in percent units: $m_T = -4.71 \pm 2.33$, $b_T = -4.4 \pm 0.6$, $m_R = 15.37 \pm 2.91$, and $b_R = 7.1 \pm 0.6$.

We translate our measured Hα EW to log $L_{\text{Lbol}}/L_{\text{bol}}$ using a grid of BT-Settl model atmospheres from Allard et al. (2011) for $T_{\text{eff}}$ in the range 2200–5000 K, assuming solar composition and log($g$) = 5.0 (appropriate for very-low-mass stars in Blanco 1). First, we compute the bolometric flux ($L_{\text{bol}}$) for these model atmospheres. Then, for a given GMOS target, we use its color to estimate $T_{\text{eff}}$ from a BCAH 135 Myr isochrone. This $T_{\text{eff}}$ is overestimated since the activity would suppress it, but this is a small effect (~0.1 dex in log $L_{\text{Lbol}}/L_{\text{bol}}$ for a ~200 K shift). We use this $T_{\text{eff}}$ to interpolate over the model atmospheres to estimate the atmospheric continuum flux at the Hα feature ($F_{\lambda_{\text{H}\alpha}}$). The Hα flux ($F_{\text{H}\alpha}$) is computed by convolving $F_{\lambda_{\text{H}\alpha}}$ with the Hα EW of our target. Finally, by computing log $F_{\text{H}\alpha}/F_{\text{bol}}$, we also obtain the equivalent log $L_{\text{H}\alpha}/L_{\text{bol}}$. Propagating the photometric uncertainty in color, we find an error of ~0.03 dex in log $L_{\text{H}\alpha}/L_{\text{bol}}$, but this is much smaller than the systematic contribution of ~0.4 dex in the transformation of color to temperature. Hence, the total systematic error for log $L_{\text{H}\alpha}/L_{\text{bol}}$ is about 0.5 dex.

From the empirical relationships, we find the percent change in $T_{\text{eff}}$ (suppression) and $R$ (inflation) as a result of magnetic activity along with the percent change in luminosity. Due to the nature of how Equations (2) and (3) were derived and calibrated, the activity corrections should only be applied to stars with Hα in emission. We then use this information to determine the 135 Myr BCAH magnitudes and colors of our Blanco 1 sample as if these stars were inactive; we remove the effects of activity.

Using the same logic as before, we set the “corrected” LDB boundaries using the corrected, inactive photometry for targets 22 and 38. We determine the LDB parameters at this new LDB location and record these values in Table 2. We infer the activity-corrected LDB is located at $I_0 = 18.45 \pm 0.16$ and $(I - K_\alpha)_0 = 2.77 \pm 0.12$, which corresponds to log($L$) = −2.818 $L_\odot$ and the BCAH LDB age of 114±10 Myr.

Figure 12 shows a closer view on the regions of the LDB for the intrinsic $I/I - K_\alpha$ CMD. This plot shows the Li detections for both the original (black points) and activity-corrected (yellow points) photometric positions. For simplicity, vectors showing the direction of the activity corrections are drawn only for targets 22 and 38, which establish the LDB boundaries in the CMD, and this is shown by the shaded boxes. The LDB positions (red stars) are marked within these boxes, and BCAH isochrones are drawn to show the age we infer from their predicted luminosities. Accounting for the effects of chromospheric activity mainly shifts the data upward along the cluster sequence. Additionally, the boundaries of the LDB are compacted when the effects of magnetic activity are removed and renders a corrected, more precise age. We carried out this same process of characterizing the LDB for $K_\alpha$ versus $I - K_\alpha$. LDB parameters derived from PMS models using $K_\alpha$ are recorded in Table 2.

Despite consistent treatments, use of the BCAH models along with DUSTY synthetic photometry renders statistically different LDB ages and parameters depending on whether we use $I_0$ or $K_{\alpha,0}$ magnitudes versus the $(I - K_{\alpha,0})$ color as presented in Table 2. For the standard BCAH results, the $I_0$ and $K_{\alpha,0}$ LDB parameter values are statistically compatible to within $1\sigma$ of their errors. Conversely, for the corrected BCAH results, the $I_0$ and $K_{\alpha,0}$ results differ greater than $1\sigma$. Further work on understanding the reason for different age and parameter determinations at the LDB depending on the choice of photometry is required.

5. SUMMARY AND CONCLUSION

In this paper, we have expanded upon the initial identification of the Blanco 1 LDB (Cargile et al. 2010). We obtain the full sample of Blanco 1 candidates for our GMOS survey and analyzed both previous and new data consistently to update the inferred LDB age. This was done by developing spectral analysis software to systematically analyze the Hα and Li features. Moreover, we analyze the Li feature using emcee to perform MCMC sampling on the Gaussian parameters that measure EW (Li). We find that for Li detections with $I > 17$, the error is reduced by up to a factor of two using MCMC as opposed to relying on the S/N estimate from Equation (1). Since the Hα region is simpler and has a higher S/N, a Gaussian fit via least-squares to the Hα line is sufficient.

Out of the 43 spectra from our GMOS survey, we find 14 high confidence low-mass members belonging to Blanco 1, and 6 of these stars exhibit detectable Li features. Based on our systematic analysis of the Li feature, we verify the findings of Cargile et al. (2010) that targets 38, 43, 45, and 49 exhibit Li absorption with a confidence >3σ. We have also obtained two new Li detections for low-mass Blanco 1 members; namely, the K-dwarf target 6335 and M-dwarf target 22. Importantly, target 22 influences how we determine the LDB age as it appears to currently be in the process of depleting its initial Li content.

Using targets 22 and 38 to establish the LDB boundaries, we derive parameters at the LDB using the “standard” technique. We first determine the LDB age of Blanco 1 using the BCAH models and synthetic photometry from the DUSTY model atmospheres, and also obtain the LDB age using the empirical bolometric corrections from P&M. Using the BCAH models and the synthetic photometry, we measure an updated standard LDB age for Blanco 1 of 126+13−9 Myr. Compared with the Pleiades (126 ± 11 Myr; Burke et al. 2004), these open clusters share remarkable coevality.
For the low-mass Blanco 1 members in our sample, empirical corrections from Stassun et al. (2012) were used to determine the amount of suppression in $T_{\text{eff}}$ and inflation in $R$ due to chromospheric activity as indicated by Hα emission. We remove these effects and determine the photometric properties of our targets as if they were not active. Using the inactive properties of targets 22 and 38, we identify a “corrected” LDB and infer a new age of $114_{-13}^{+10}$ Myr from BCAH models.

This corrected age for Blanco 1 brings the LDB age and MSTO isochrone age ($r_t$ isochrone fitting with moderate convective-core overshoot; Naylor & Jeffries 2006; Naylor 2009) into close agreement ($\sim 110$ Myr; D. J. James et al. in preparation). On the other hand, the gyrochronology method from Cargile et al. (2014) determined the age of Blanco 1 to be $146_{-14}^{+13}$ Myr. Understanding the reasons for this disagreement is beyond the scope of this paper.

We find that applying empirical relationships to account for magnetic activity slightly increases the LDB luminosity, and subsequently results in a $\sim 10\%$ decrease in the predicted age. This systematic is comparable to the typical measurement error quoted by other LDB age determinations (e.g., Burke et al. 2004) but has not been included in any previous LDB study. Our work prompts the need to reinvestigate previous LDB determinations in an effort to produce more accurate ages, and recalibrate the stellar age scale relying on LDB ages.

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APPENDIX

In Table 3, we reported observational and empirical data associated with objects observed with GMOS but determined to be cluster non-members (see Section 3.3).
REFERENCES

Allard, F., Homeier, D., & Freytag, B. 2011, in ASP Conf. Ser. 448, 16th Cambridge Workshop on Cool Stars, Stellar Systems, and the Sun, ed. C. Johns-Krull, M. W. Brown, & A. A. West (San Francisco, CA: ASP), 91

Allen, L. E., & Strom, K. M. 1995, AJ, 109, 1379

Baraffe, I., Chabrier, G., Allard, F., & Hauschildt, P. H. 1998, A&A, 337, 403

Baraffe, I., Chabrier, G., Allard, F., & Hauschildt, P. H. 2002, A&A, 382, 563

Barrado y Navascués, D., Stauffer, J. R., & Patten, B. M. 1999, ApJL, 522, L53

Basri, G. 1997, MmSAI, 68, 917

Basri, G., Marcy, G. W., & Graham, J. R. 1996, ApJ, 458, 600

Bildsten, L., Brown, E. F., Matzner, C. D., & Ushomirsky, G. 1997, ApJ, 482, 442

Bochanski, J. J., West, A. A., Hawley, S. L., & Covey, K. R. 2007, AJ, 133, 531

Bodenheimer, P. 1965, ApJ, 142, 451

Briceño, C., Hartmann, L., Stauffer, J., & Martín, E. 1998, AJ, 115, 2074

Burke, C. J., Pinsonneault, M. H., & Sills, A. 2004, ApJ, 604, 272

Cargile, P. A., James, D. J., & Jeffries, R. D. 2010, ApJL, 725, L111

Cargile, P. A., James, D. J., Pepper, J., et al. 2014, ApJ, 782, 29

Carlsson, M., Rutten, R. J., Bruls, J. H. M. J., & Shchukina, N. G. 1994, A&A, 288, 860

Casagrande, L., Ramírez, I., Meléndez, J., Bessell, M., & Asplund, M. 2010, A&A, 512, A54

Cayrel, R. 1988, in IAU Symp 132, The Impact of Very High S/N Spectroscopy on Stellar Physics, ed. G. Cayrel de Strobel & M. Spite (Dordrecht: Kluwer), 345

Chabrier, G., & Baraffe, I. 1997, A&A, 327, 1039

Ford, A., Jeffries, R. D., & Smalley, B. 2005, MNRAS, 364, 272

Foreman-Mackey, D., Hogg, D. W., Lang, D., & Goodman, J. 2013, PASP, 125, 306

González, J. F., & Levato, H. 2009, A&A, 507, 541

Hook, I. M., Jørgensen, I., Allington-Smith, J. R., et al. 2004, PASP, 116, 425

Jeffries, R. D., & James, D. J. 1999, ApJ, 511, 218

Jeffries, R. D., Naylor, T., Devey, C. R., & Totten, E. J. 2004, MNRAS, 351, 1401

Jeffries, R. D., Naylor, T., Mayne, N. J., Bell, C. P. M., & Littlefair, S. P. 2013, MNRAS, 434, 2438

Jeffries, R. D., & Oliveira, J. M. 2005, MNRAS, 358, 13

López-Morales, M. 2007, ApJ, 660, 732

Maeder, A. 1974, A&A, 32, 177

Mermilliod, J.-C., Platais, I., James, D. J., Grenon, M., & Cargile, P. A. 2008, A&A, 485, 95

Montes, D., Martín, E. L., Fernandez-Figueroa, M. J., Corone, M., & de Castro, E. 1997, A&A, 123, 473

Morales, J. C., Ribas, I., & Jordi, C. 2008, A&A, 478, 507

Moraux, E., Bouvier, J., Stauffer, J. R., Barrado y Navascués, D., & Cuillandre, J.-C. 2007, A&A, 471, 499

Naylor, T. 2009, MNRAS, 399, 432

Naylor, T., & Jeffries, R. D. 2006, MNRAS, 373, 1251

Oliveira, J. M., Jeffries, R. D., Devey, C. R., et al. 2003, MNRAS, 342, 651

Panagi, P. M., & O'dell, M. A. 1997, A&AS, 121, 213

Pavlenko, Y. V., & Magazzu, A. 1996, A&A, 311, 961

Pavlenko, Y. V., Rebolo, R., Martín, E. L., & Garcia Lopez, R. J. 1995, A&A, 303, 807

Pecaut, M. J., & Mamajek, E. E. 2013, ApJS, 208, 9

Platais, I., Girard, T. M., Vieira, K., et al. 2011, MNRAS, 413, 1024

Ribas, I. 2006, Ap&SS, 304, 89

Soderblom, D. R. 2010, ARA&A, 48, 581

Soderblom, D. R., Hillenbrand, L. A., Jeffries, R. D., Mamajek, E. E., & Naylor, T. 2013, arXiv:1311.7024

Soderblom, D. R., Jones, B. F., Balachandran, S., et al. 1993, AJ, 106, 1059

Stassun, K. G., Kratter, K. M., Scholz, A., & Dupuy, T. J. 2012, ApJ, 756, 47

Stauffer, J. R., Hartmann, L. W., Fazio, G. G., et al. 2007, ApJS, 172, 683

Stauffer, J. R., Schultz, G., & Kirkpatrick, J. D. 1998, ApJL, 499, L199

Ushomirsky, G., Matzner, C. D., Brown, E. F., et al. 1998, ApJ, 497, 253

van Leeuwen, F. 2009, A&A, 497, 209

Zapatero Osorio, M. R., Bejar, V. J. S., Pavlenko, Y., et al. 2002, A&A, 384, 937