The Lithium Depletion Boundary and the Age of the Young Open Cluster IC 2391

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ABSTRACT

In previous programs, we have identified a large number of possible very low mass members of the young, open cluster IC 2391 based on their location in an $I$ versus $(R-I)_c$ color-magnitude diagram. We have now obtained new photometry and intermediate resolution ($\Delta \lambda = 2.7 \text{ Å}$) spectra of 19 of these objects ($14.9 \leq I_c \leq 17.5$) in order to confirm cluster membership. We identify 15 of our targets as likely cluster members based on their $VRI$ photometry, spectral types, radial velocity, and H$\alpha$ emission strengths. Higher S/N spectra were obtained for 8 of these probable cluster members in order to measure the strength of the lithium 6708 Å doublet and thus obtain an estimate of the cluster’s age. One of these 8 stars has a definite lithium detection and two other (fainter) stars have possible lithium detections. A color-magnitude diagram for our program objects shows that the lithium depletion boundary in IC 2391 is at $I_c=16.2$. Using recent theoretical model predictions, we derive an age for IC 2391 of $53\pm5$ Myr. While this is considerably older than the age most commonly attributed for this cluster ($\sim35$ Myr) this result for IC 2391 is comparable those recently derived for the Pleiades and Alpha Persei clusters and can be explained by new models for high mass stars that incorporate a modest amount of convective core overshooting.

Subject headings: stars: low mass, brown dwarfs, open clusters and associations: IC 2391
1. Introduction

Measurement of the location of the “lithium depletion boundary” (LDB) offers a new method to determine the age of young open clusters that is claimed to be more accurate and less subject to possible systematic errors than any other means (c.f., Bildsten et al. 1997; Basri 1997; Ventura et al. 1998a,b; Ushomirsky et al. 1998). The LDB method was first applied to the Pleiades cluster (Basri, Marcy, & Graham 1996; Rebolo et al. 1996), with the most recent determination (Stauffer, Schultz, & Kirkpatrick 1998) yielding an age of 125±8 Myr. That age is considerably older than some estimates of the Pleiades age, but consistent with other estimates which assume a modest amount of convective core overshoot (Ventura et al. 1998a,b). Our group has now obtained LDB ages for two other open clusters – Alpha Persei (Stauffer et al. 1999 –see also Basri & Martín 1999) and IC 2391. We report the results for IC 2391 in this paper.

Located at a distance of about ∼155 pc, IC 2391 (α=8h40.2m, δ=−53°04’, J2000.0) is the fifth nearest cluster to the Sun. The first faint proper motion survey of this cluster was obtained by Stauffer et al. (1989), yielding 9 previously undiscovered late-type members. Patten & Simon (1996) used data from ROSAT to obtain a more complete membership list by combining the X-ray data with ground-based optical photometry and spectroscopy. Additional spectroscopic studies by Stauffer et al. (1997) confirmed that the cluster is relatively young based on rotational velocities, lithium abundances and chromospheric activity for G, K and early M dwarfs. However, none of those studies provided cluster members extending faint enough (I > 15) to be suitable for the LDB test. Recently, Patten & Pavlovsky (1999) and Barrado y Navascués et al. (1999a) have provided lists of faint candidate members of IC 2391 which may extend to low enough mass. Spectra of some of these candidates are used here to determine the location of the LDB in IC 2391.
2. Observations and Data Reduction

Spectroscopic observations of the most promising candidate low-mass members of the cluster were carried out with the 4m telescope at CTIO during 9–11 January 1999. We used the R-C spectrograph with the Blue Air Schmidt camera, the KPGLD grating (790 l/mm), the Loral 3K CCD, and a one arcsec slit. This configuration yielded a spectral resolution of 2.7 Å and a free spectral range of 6295–8815 Å.

The primary targets for our observations were selected from the optical survey by Barrado y Navascués et al. (1999a), which identified several dozen very low mass stars and brown dwarf candidates based primarily on $R_c, I_c$ photometry. The targets were selected to have apparent magnitudes near to or below the expected location of the LDB in IC 2391 using the nominal age and distance to the cluster and the theoretical model predictions of Chabrier & Baraffe (1997). Additional $V$ filter data, obtained at the CTIO 0.9m telescope using the Tektronix 2K #3 camera during 4–6 January 1999, allowed us to refine the target list based on their location in a $[(V - R_c), (R - I)_c]$ color-color diagram. Near infrared data from the 2MASS project (Adams 1998) for some of our objects were also used to refine the target list. Additional details can be found in Barrado y Navascués et al. (1998, 1999a). Several, presumably higher mass objects, were added to our target list from the surveys of Patten & Pavlovsky (1999) and Patten & Simon (1996). We also observed several Gliese stars of spectral types M0–M6 and BRI 0021-0214, a M9.5 spectral type dwarf (Basri & Marcy 1995), in order to serve as template objects with which to compare the IC 2391 spectra. For the IC 2391 low-mass candidates, the exposure times ranged from 10 minutes to 4.5 hours. The data were reduced using standard routines within the IRAF².

²IRAF is distributed by National Optical Astronomy Observatories, which is operated by the Association of Universities for Research in Astronomy, Inc., under contract to the National Science Foundation, USA
3. Analysis

We have determined equivalent widths and line profiles for our program stars for several spectral features, namely Hα in emission, Li I 6708Å, and the K I and Na I doublets (7665/7699 and 8183/8195 Å, respectively). In addition, we have measured several spectral indices, namely PC1, PC2 and PC3 at 6525-7050Å, 7030-7580Å, and 7540-8265Å, respectively (Martín, Rebolo, & Zapatero-Osorio 1996); VO at 7350-7560Å (Kirkpatrick, Henry, & Simons 1995); and TiO, CaH at 6510-7050 Å (Martín & Kun 1996), in order to estimate spectral types and \((R-I)_C\) colors. These estimates were achieved by a calibration based on a group of cool dwarfs of known spectral types and colors. The derived spectral types are estimated to have an uncertainty of 0.5 or 1 subclass. Radial velocity estimates were derived for the program stars by two methods: (1) by cross-correlation versus the spectra of GJ285 and GJ406 and (2) by measurement of the wavelength of the Hα emission line. The radial velocity errors for the cross-correlation method are estimated to range from 10 to 50 km/s. The uncertainty in the radial velocity derived from the fit to the Hα profile should be \(\sim 15\) km/s for most of our objects based on the repeatability in the measured position of OH night-sky emission lines of similar strength in the sky spectra. Table 1 lists the names of our targets, along with the photometry (Barrado y Navascués et al. 1999a) and the spectroscopic results.

3.1. Membership Criteria

In the last column of Table 1, we provide an estimate of the membership status for each of our target stars. This status was determined by consideration of the following criteria:

(1) A comparison of the photometrically measured \((R-I)_C\) color and the color estimated from the spectral type, assuming \(E(R-I)_C \sim 0.01\) for IC 2391 (e.g., Hogg 1960; Patten & Simon
was used to eliminate background objects.

2) Radial velocities were compared with the cluster average of \( \sim 15 \) km/sec (Stauffer et al. 1997).

3) H\( \alpha \) equivalent widths were compared with typical values for field stars and Pleiades members.

4) The strength of the gravity dependent Na I 8200Å doublet, strong in dM, weaker in PMS M, and very weak in M-type giants (Martín, Rebolo, & Zapatero-Osorio 1996), was used to eliminate background giants and nearby field stars (see Figure 1).

These criteria allowed us to reject two stars as members of the cluster and to classify another two stars as possible non-members. CTIO-040 and CTIO-094 have radial velocities less than 3 km/s. For these two stars, the difference in their photometrically measured \((R-I)_C\) color and the color estimated from the spectral type is 0.17 and 0.24 magnitudes respectively. Both of these stars also have H\( \alpha \) in absorption. In the spectral type range we have covered, all members of the Pleiades have H\( \alpha \) in emission with EW\( \sim 2-10 \) Å (Stauffer, Liebert, & Giampapa 1995). Because IC 2391 is younger, we expect to see similar or stronger H\( \alpha \) emission from our candidates. Therefore we consider CTIO-040 and CTIO-094 to be nearly certain non-members. The targets CTIO-081 and CTIO-106 were found to have radial velocities less than 3 km/s. These stars are considered possible non-members. The remaining 15 targets in our sample appear to be young, PMS objects and thus are likely members of the IC 2391 cluster.

3.2. The Lithium Depletion Boundary in IC 2391

Figure 2 shows the region around the lithium doublet for three members whose \( I \) magnitudes place them near the LDB – PP14, CTIO-096, and CTIO-038. The spectrum of
GJ406, an M6V star without lithium, is shown for comparison purposes. Clearly, CTIO-038 ($I_c=16.29$) contains lithium, whereas PP14, 0.46 magnitudes brighter, does not have a discernible feature at 6708Å. CTIO-096, slightly brighter than CTIO-038, has also apparently depleted all of its lithium. We also have low signal-to-noise, possible detections of lithium in two other candidate members of IC 2391 (CTIO-041 and CTIO-062), both of which are fainter and redder than CTIO-038. Other candidate cluster members, brighter and warmer than CTIO-038 and observed at high S/N, do not show lithium in their spectra (see Table 1).

Figure 3 shows an $I_c/(R-I)_c$ color-magnitude diagram for our sample of candidates. Based on the detection of lithium in CTIO-038 and the non-detection of lithium in CTIO-096, we can estimate the location of the LDB in IC 2391 to be at $I_c=16.2\pm0.15$, $(R-I)_c=1.91$.

Using the evolutionary models of Baraffe et al. (1998), we can estimate the age of IC 2391 using the position of LDB. Following Figure 3 of Stauffer, Schultz, & Kirkpatrick (1998), we have converted the $I_c$ magnitude of the LDB into an age, assuming an interstellar absorption of $A_I=0.02$ and a distance modulus of $(m-M)_0=5.95\pm0.13$ yielding $M_I=10.25$ which implies an age of 53±5 Myr. While this value of the cluster’s age is significantly larger than previous estimates (∼35 Myr), this correction factor to the classical age is consistent with those estimated for other young open clusters, such as the Pleiades (Stauffer, Schultz, & Kirkpatrick 1998) and α Persei (Stauffer et al. 1999), using the LDB method.

3This value for the distance of IC 2391 represents a compromise between various determinations of the distance modulus and Hipparcos parallaxes. See, for example, Becker & Fenkart (1971), Lynga 1987, Patten & Pavlovsky (1999), and Robichon et al. (1999) for additional details.
3.3. The Lowest Mass Members of IC 2391

At an age of 53 Myr, a star at the LDB should have a mass of $\sim0.12\ M_\odot$ (Chabrier & Baraffe 1997). The corresponding $I_c$ magnitude for a 0.075 $M_\odot$ object (i.e., an object at the transition boundary between the stellar and sub-stellar domains) in IC 2391 is then $M_I \sim 11.15$. If the latter estimate is correct, then the faintest two candidate members in IC 2391 that we have observed spectroscopically (CTIO-061 and CTIO-113) would be brown dwarfs.

4. Discussion

The ages for young open clusters have been controversial for many years due to uncertainties in the amount of convective core overshoot to include in models of high mass stars. Although an age scale for clusters using models without convective core overshoot has generally been adopted (Patenaude 1978; Mermilliod 1981), models which incorporate a relatively large convective core overshoot parameter, yielding cluster ages up to twice as old as the no-overshoot models, have also been advocated (Mazzei & Pigatto 1988). Without additional observational data, it has been difficult to choose between these age scales. The lithium depletion age method provides the means to resolve this debate. We now have lithium depletion ages for three open clusters: the Pleiades (Stauffer, Schultz, & Kirkpatrick 1998), Alpha Persei (Basri & Martín 1999; Stauffer et al. 1999), and IC 2391 (this paper). When compared to the non-overshoot model ages of Mermilliod (1981), the ratio of the LDB age determination to the non-overshoot model age is 1.61, 1.65, and 1.46 for Pleiades, Alpha Persei and IC 2391, respectively. This suggests that (a) some convective-core overshoot is needed in evolutionary models for high-mass stars and (b) the amount of convective-core overshoot is not a strong function of mass (at least in the mass range sampled at the turn-off of these three clusters). A revised age scale for open clusters would have important implications for a variety of stellar evolution topics including, for example, the empirical (and
theoretical) correlations between lithium abundance, coronal activity, and rotation rate as a function of age for low mass stars.

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Figure Captions

Fig. 1.— Na I 8200 Å equivalent width versus spectral type. Field dwarfs are shown as solid circles and IC 2391 members are shown as open circles. Stars initially identified as candidate IC 2391 members but subsequently rejected as members using the membership criteria outlined in §3.1 appear as crosses.

Fig. 2.— Spectra of IC 2391 candidates (solid lines). We only show here the spectral region around the Li I 6708 Å doublet (vertical dashed line). For comparison, GJ406, field M6 dwarf with no lithium, is also plotted (dotted line).

Fig. 3.— Color-magnitude diagram of IC 2391. Probable members observed at low S/N appear as plus symbols (+), whereas members observed at high S/N are displayed as circles (solid if lithium was detected, open if not). Solid triangle symbols indicate probable lithium detections. Non-members appear as × symbols). The location of the LDB is indicated, as well as a ZAMS (solid line) and 50 and 30 isochrones (dashed lines).
Field stars
Non-members
Members
IC2391

- Member, Li detection
- Member, Li probable
- Member, No Li
- Member, Low S/N
- Non Member.

Lithium Depletion Boundary
## Table 1

Data for IC 2391 Very Low Mass Stars and Brown Dwarf Candidates

| Name\(^1\) | \(V\) | \(I_c\) | \((R-I)_{c}\) | \(\text{EW} (\text{Na I})\) | \(\text{EW} (\text{H\alpha})\) | \(\text{RV}\) | Spectral Type | \(\text{Li i}\) | Member |
|---------|------|------|-------------|----------------|----------------|---------|-------------|--------|--------|
| VXR27   | 13.97 | 11.51 | 1.33       | 1.30           | -              | <0      | -           | -      | -\(^3\) M2.5 | N   | N   |
| VXR71a  | 15.29 | 12.90 | 1.33       | 1.40           | -              | 4.9     | -25         | -9     | M3     | N   | Y,SB? |
| CTIO-152 | 18.11 | 14.89 | 1.78       | 1.65           | 5.1            | 9.9     | 31          | 25\(^2\) | M4     | N   | Y   |
| PP11    | 18.48 | 15.30 | 1.79       | 1.75           | 4.7            | 5.4     | 19          | 25\(^2\) | M4.5   | N   | Y   |
| CTIO-094 | 18.27 | 15.31 | 1.74       | 1.50           | 4.9            | <0      | -           | 24\(^2\) | M3.5   | -   | N   |
| PP14    | 19.22 | 15.83 | 1.87       | 1.85           | 4.8            | 6.3     | 18          | 17\(^2\) | M5     | N   | Y   |
| CTIO-136\(^5\) | 19.72 | 15.87 | 1.98       | 1.85           | 5.2            | 6.1     | 31          | 27\(^2\) | M5.5\(^4\) | -   | Y   |
| CTIO-017 | 19.30 | 15.99 | 1.75       | 1.70           | 5.6            | 11.0    | 4           | 9\(^2\)  | M4\(^4\) | -   | Y   |
| CTIO-039 | 19.47 | 16.05 | 1.82       | 1.70           | 5.6            | 49.5/18.8 | 106/42     | 18/25\(^6\) | M4 | N   | Y   |
| CTIO-096\(^7\) | 19.75 | 16.14 | 1.91       | 1.90           | 5.3            | 8.7     | 31          | 22     | M5     | N   | Y   |
| CTIO-205 | 20.21 | 16.21 | 2.07       | 2.00           | 5.2            | 8.0     | -14         | 8\(^2\)  | M5.5\(^4\) | -   | Y?  |
| CTIO-038 | 19.90 | 16.29 | 1.91       | 1.90           | 5.1            | 7.0     | 15          | 14\(^2\) | M5     | Y   | Y   |
| CTIO-077 | 20.04 | 16.31 | 1.93       | 1.85           | 5.1            | 7.0     | 48          | 19\(^2\) | M5     | -   | Y   |
| CTIO-081 | 20.38 | 16.47 | 2.08       | 2.05           | 5.8            | 8.6     | 3           | 2\(^2\)  | M5.5   | -   | Possible |
| CTIO-041 | 20.46 | 16.55 | 1.92       | 1.95           | 5.2            | 8.7     | 34          | 15\(^2\) | M5     | Y   | Y   |
| CTIO-106 | -     | 16.36 | 2.01       | 1.90           | 5.8            | 14.1    | 3\(^2\)     | -1\(^2\) | M5.5   | -   | Possible |
| CTIO-062 | 20.84 | 16.75 | 2.05       | 1.95           | 5.3            | 6.6/7.9  | 10/7       | 13/11\(^6\) | M6\(^4\) | Y   | Y   |
| CTIO-145 | -     | 16.94 | 2.14       | 2.15           | 5.5            | 7.9     | 11          | 13\(^2\) | M6     | -   | Y   |
| CTIO-113 | 21.88 | 17.28 | 2.14       | -              | 6.3            | 4.6     | 11          | -1\(^2\) | M7\(^4\) | -   | Y   |
| CTIO-061 | -     | 17.31 | 2.14       | 2.10           | 5.9            | 2.3     | 46          | 24\(^2\) | M6\(^4\) | -   | Y   |
| CTIO-040 | 21.65 | 17.46 | 2.12       | 1.95           | 6.2            | <0      | -           | 0\(^2\)  | M6\(^4\) | -   | N   |

Equivalent widths (EW) are given in units of Å. Radial velocities are given in units of km/s.

\(^1\)VXR: Patten & Simon (1996) and Simon & Patten (1997), CTIO: Barrado y Navascués et al. (1999a), PP: Patten & Pavlovsky (1999).

\(^2\)A colon designates estimated error > 25 km/s.

\(^3\)From Stauffer et al. (1997).

\(^4\)Uncertainty of 1 subclass in the derived spectral type.

\(^5\)Also known as PP17.

\(^6\)EW(\text{H\alpha}) and RV for 2 consecutive nights.

\(^7\)Also known as VXRP32h.