A lithium depletion boundary age of 21 Myr for the Beta Pictoris moving group

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ABSTRACT
Optical spectroscopy is used to confirm membership for 8 low-mass candidates in the young Beta Pic moving group (BPMG) via their radial velocities, chromospheric activity and kinematic parallaxes. We searched for the presence of the Li I 6708Å resonance feature and combined the results with literature measurements of other BPMG members to find the age-dependent lithium depletion boundary (LDB) – the luminosity at which Li remains unburned in a coeval group. The LDB age of the BPMG is $21 \pm 4$ Myr and insensitive to the choice of low-mass evolutionary models. This age is more precise, likely to be more accurate, and much older than that commonly assumed for the BPMG. As a result, substellar and planetary companions of BPMG members will be more massive than previously thought.

Key words: stars: kinematics, open clusters and associations: individual: Beta Pictoris

1 INTRODUCTION
The Beta Pic Moving Group (BPMG) is a young, kinematically coherent group of a few dozen stars within ~ 50 pc of the Sun. Members have been examined via their radial velocities, chromospheric activity, parallaxes, and spatial resolution. Young gas giant planets around MG members are expected to be more luminous than in older systems, and young stars are frequently surrounded by debris discs that may evidence the formation of terrestrial planets or provide diagnostics of unseen planets. Studies that exploit the youth and proximity of BPMG members include: the identification and direct imaging of a planet (e.g. Lagrange et al. 2010, 2012; Bonnefoy et al. 2011, 2013) and debris disc (e.g. Smith & Terrile 1984; Holland et al. 1998; Golimowski et al. 2006) around its most luminous member, the A0 star $\beta$ Pic; systematic surveys for planets, gas and debris discs using high angular resolution imaging or infrared diagnostics (e.g. Brandt et al. 2013; Wahhaj et al. 2013; Dent et al. 2013); and testing low-mass stellar and substellar evolutionary models using spatially resolved binary systems (Biller et al. 2010; Mugrauer et al. 2010).

All such investigations require age estimates for BPMG members, either to place them in context with observations of other coeval groups or to compare them with models for stars, discs and planets at an absolute age – for example to estimate masses (or detection limits) of planetary companions from their luminosities. If BPMG membership is established, then a common, coeval origin is usually assumed with other members, and the age of the ensemble is estimated using the same techniques available for young clusters. The BPMG age is commonly assumed to be ~ 12 Myr. Estimates based on the positions of low-mass stars in the Hertzsprung-Russell diagram (HRD) are $20 \pm 4$ Myr (Jeffries et al. 2013) and $12 \pm 4$ Myr (Zuckerman et al. 2001). Some estimates of kinematic ages, based on the traceback of candidate members to their smallest volume, also yield 10-12 Myr with very small formal uncertainties (Ortega et al. 2002, 2004; Song et al. 2003). However, Makarov (2007) finds a much less precise $22 \pm 12$ Myr.

In this Letter we estimate an age for the BPMG based on the lithium depletion boundary (LDB). In low-mass stars Li is burned rapidly once PMS contraction raises core temperatures to ~ $3 \times 10^6$ K. Convective mixing ensures that Li is then depleted throughout the star, including the photosphere. The age at which this occurs is mass-dependent and thus, in a coeval group, the luminosity of a sharp transition between faint stars that retain their initial Li and only slightly more luminous stars that are entirely depleted, can be used to estimate the group age (e.g. Bildsten et al. 1997). In contrast with ages determined from isochrone fitting in the HRD, the LDB technique has little model dependence (Burke et al. 2004) and has been used to estimate the ages of several young clusters with ages < 40 Myr that are comparable to the BPMG (NGC 1960 with age $22 \pm 4$ Myr - Jeffries et al. 2013; IC 4665 with age $28 \pm 5$ Myr - Manzi et al. 2008; NGC 2547 with age $35 \pm 3$ Myr - Jeffries & Oliveira 2005). New observations presented here allow us to confirm membership for previously proposed low-mass BPMG candidates, assess their Li content and determine an accurate LDB age for the group.

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between measured and predicted RVs (for group membership, available, otherwise the “kinematic distance” – see Section 3.1) and a spectral type. Indications of photospheric Li abundance using the Li $\alpha$ line were subject to relative flux-calibration and telluric correction.

Table 1. Confirmed BPMG members with their photometry (from UCAC4 – Zacharias et al. 2013; 2MASS – Cutri et al. 2003), radial velocities (RV), difference between measured and predicted RVs (for group membership, $\Delta$RV), equivalent widths of Hα and Li $\alpha$ 6708 Å, distance (from a trigonometric parallax where available, otherwise the “kinematic distance” – see Section 3.1) and a spectral type.

| Name (2MASS) | Ref | HJD 2455000+ | V mag | J mag | K mag | RV $\pm$1kms$^{-1}$ | $\Delta$RV $\pm$1kms$^{-1}$ | Hα EW $\pm$1mA | Li EW $\pm$1mA | distance $\pm$1pc | SpT $\pm$1M$^{-1}$ |
|--------------|-----|--------------|-------|-------|-------|----------------------|----------------------|----------------|----------------|-----------------|----------------|
| J01351393−0712517 M13 | 6290.625 | 13.43 | 8.96 | 8.08 | 6.5 $\pm$ 1.8$^d$ | 2.7 | $-6.1$ | $<23$ | 37.9 $\pm$ 2.4$^h$ | 4.0 |
| J02175601+1225266 S12 | 6291.572 | 14.09 | 9.96 | 9.08 | 7.0 $\pm$ 1.3 | 1.4 | $-4.2$ | $<22$ | 67.9 $\pm$ 6.1 | 4.0 |
| J05015881 | 6372.435 | 12.42 | 8.56 | 7.70 | 22.0 $\pm$ 1.3 | 3.2 | $-2.8$ | $<49$ | 41.9 $\pm$ 3.3 | 2.9 |
| J16430128−1754274 M13 | 6375.736 | 12.57 | 9.44 | 8.55 | $-10.0 $ $\pm$ 1.5$^e$ | 3.5 | $-1.6$ | 364 $\pm$ 21$^b$ | 59.2 $\pm$ 2.8 | 0.6 |
| J05015881+0958587a | 6375.354 | 11.51 | 7.21 | 6.37 | 18.8 $\pm$ 1.5$^f$ | 2.9 | $-4.6$ | $<53^l$ | 24.9 $\pm$ 1.3 | 4.1 |
| J05022729−2101444 M13 | 6377.361 | 14.41$^g$ | 9.72 | 8.83 | 22.8 $\pm$ 3.8 | 2.0 | $-12.9$ | 618 $\pm$ 43 | 30.5 $\pm$ 4.9 | 5.6 |
| J19102820−2319486 M13 | 6377.767 | 13.22 | 9.10 | 8.22 | $-8.0 $ $\pm$ 1.7 | 3.8 | $-4.8$ | $<55$ | 69.2 $\pm$ 3.4 | 4.0 |

Notes. Targets from M13 = Malo et al. (2013), S12 = Schröder et al. (2012). Unresolved binary systems: (a) M3.0+M3.0 and (b) M4.0+M4.5 (Malo et al 2013), (c) Photometry from the NOMAD Catalog (Zacharias et al. 2005), $\sigma_V = 0.3$ assumed. RVs previously measured: (d) 11.7 $\pm$ 5.3 kms$^{-1}$ (Shkolnik et al. 2012), (e) $-11.3 \pm 3$ kms$^{-1}$ (Zwitter et al. 2008), (f) 14.9 $\pm 3.5$ kms$^{-1}$ (Kharchenko et al. 2007), (g) 20.5 $\pm$ 4.0 kms$^{-1}$ (Malo et al. 2013). Li EW values previously reported: (h) 300 mA (Kiss et al. 2011), (i) 0 (da Silva et al. 2009), (j) 223 mA (Malo et al. 2013). Distances from trigonometric parallaxes: (k) Shkolnik et al. (2012) and (l) Malo et al. (2013); we derive kinematic distances of 37.7 $\pm$ 4.3 and 33.2 $\pm$ 3.7 pc, respectively.

2 NEW LOW-MASS CANDIDATES, OBSERVATIONS, AND DATA REDUCTION

Indications of photospheric Li abundance using the Li $\alpha$ 6708 Å line are available for a few low-mass BPMG members, but are sparse in the critical region close to the expected LDB location at 10-30 Myr (spectral types M4–M5 – Mentuch et al. 2008; Yee & Jensen 2010). We have obtained new spectroscopy of M-type BPMG candidates with brightnesses of 10.6 < V < 14.6, and spectral-type M (V – K > 4). Targets were taken from probable members listed in the proper-motion-based surveys of Schröder et al. (2012), Shkolnik et al. (2012) and Malo et al. (2013). The spectroscopy is used to confirm kinematic membership with a radial velocity measurement and ascertain the presence or not of Li. Spectroscopy was also obtained for a sample of M dwarf candidates in the AB Doradus MG. The full details of all targets and measurements will be presented in a subsequent paper; in this Letter, we focus on BPMG candidates that emerged as likely members. The results of the analyses for these stars are summarised in Table 1.

Targets were observed on 28-29 December 2012 using the 2.56-m Nordic Optical Telescope (NOT) and Fibre-fed Echelle Spectrograph (FIES, R ~ 46000), calibrated with simultaneous ThAr lamp spectra. Spectra covering the range $\lambda \lambda 6360-7260$ Å were flat-fielded, extracted, wavelength calibrated and blaze-corrected using FIES TOOL (Stempels 2005). A second observing run on 20-26 March 2013 used the 2.5-m Isaac Newton Telescope (INT) and Intermediate Dispersion Spectrograph. The H$\beta$000V grating and a 1.4 arcsec slit gave a 2-pixel resolution of 0.7 Å in the range $\lambda \lambda 6700-7170$ Å. INT spectra were bracketed with CuNe lamp exposures and extracted and wavelength calibrated using standard tasks from the IRAF package.

Radial velocity (RV) template stars were observed during twilight on each night. Spectrophotometric and telluric standards were observed to allow for relative flux-calibrations and telluric correc-
tion of the INT spectra. Heliocentric RVs were calculated by cross-correlation with template stars using the FXCOR procedure in IRAF. RV uncertainties were obtained by combining standard errors in the RV measurements (from multiple wavelength regions and multiple exposures) with systematic uncertainties estimated from multiple measurements of RV standards.

Li \( \lambda 6708 \) Å and H\( \alpha \) equivalent widths (EWs) were measured relative to a pseudo-continuum using the SPLOT procedure in IRAF. No attempt was made to deblend Li from the weak (EW\( \sim \) 20 mA) neighbouring Fe line at 6707.4 Å. EW uncertainties were approximated as \( 1.6 \times \sqrt{\text{FWHM} \times \text{SNR}} \), where FWHM, \( p \) and SNR are the full-width half maximum of the measured line and pixel size (in Å), and the signal-to-noise ratio respectively (Cavrel 1988). If no Li feature was seen, an upper limit was estimated as twice this uncertainty assuming a FWHM of 0.7 Å.

Spectral-types were determined from the TiO molecular band flux ratio \( f(\lambda \lambda 7125-7136\text{Å})/f(\lambda \lambda 7042-7046\text{Å}) \). This ratio is calibrated for spectral types of K5–M7 (Gray 1992). A comparison of our spectral types versus \( V-K \) colour with those of known BPMG members with spectral types from Zuckerman & Song (2004) and Malo et al. (2013), suggests our calibration is consistent with literature values and that the precision is about half a subclass.

### 3 ANALYSIS

#### 3.1 Membership selection

The mean Galactic space motion of the BPMG (U, V, W) = (−11, −16, −9 km s\(^{-1}\)) and convergent point (05h 19m 48s, −60d 13m 12s, Zuckerman & Song 2004), leads to a predicted RV for group members as a function of their sky position. For 8 candidates we found the difference between this predicted RV and the measured RV (\( \Delta \text{RV in Table 1} \)) was \( < 5 \) km s\(^{-1}\) which, in common with previous work (e.g., Schlieder et al. 2012), we adopt as a required membership criterion. In addition, we require that an M-type member of the BPMG has H\( \alpha \) in emission, due to the strong chromospheric activity of such young stars. Finally, the predicted tangential velocity of a BPMG candidate combined with its proper motion, taken from the source paper listed in Table 1, leads to a “kinematic distance”. For 2 of the 8 candidates that pass the RV and H\( \alpha \) tests, there is a trigonometric parallax that agrees reasonably well with this kinematic distance. For the rest, we demand that when plotted on an absolute magnitude versus colour diagram using the kinematic distance, that candidates lie on or above the sequence defined by previously known members. Some latitude is allowed above the sequence, because targets may be unresolved binaries (two are known to be – see Table 1) up to 0.75 mag brighter than single stars of similar colour.

The colour-absolute–magnitude and spectral-type–magnitude diagrams are shown in Fig. 2. Our probable BPMG members are supplemented with previously known members (from Torres et al. 2006; Mentuch et al. 2008; Yee & Jensen 2010; Malo et al. 2013), all of which also satisfy the RV criterion discussed above. All 8 candidates that pass the RV and H\( \alpha \) tests are also consistent with the BPMG sequence and we will assume they are BPMG members.

#### 3.2 Locating the LDB

In M-dwarfs, the Li \( \lambda 6708 \) Å feature is expected to be strong where no depletion has occurred (EW\( \sim 0.6 \) Å, Palla et al. 2007) and is observed to have this strength in very young T-Tauri stars (e.g., Sergison et al. 2013). Li-burning should begin at spectral types M2–M3 after \( \sim 10 \) Myr. Within a few Myr these stars should deplete Li by factors \( > 100 \), resulting in an EW \( < 0.2 \) Å, and Li burning progresses towards cooler, less luminous stars. The most model-independent way to define the LDB age (see Jeffries 2006), is to find the luminosity where M-type BPMG members make the tran-
sition from having depleted their Li by factors > 100, to having undepleted Li at only slightly lower luminosities.

This is illustrated in Fig. 2 where we show the absolute $K$ magnitudes of Li-rich and Li-poor objects (EW < 0.2 Å) as a function of age and spectral type. Overplotted are curves of constant luminosity corresponding to the LDB (99 per cent Li depletion) at several ages. These are obtained from theoretical models of Siess et al. (2000, models with metallicity Z = 0.02) and transformed to absolute $K$ magnitudes using quartic relationships fitted to tables of bolometric corrections for PMS stars as a function of colour or spectral type (Pecaut & Mamajek 2013). In each diagram there is a reasonably clear boundary between Li-rich and Li-poor BPMG members. We identify the LDB as a rectangular region separating Li-poor from Li-rich stars. The upper bound is defined by the faintest Li-depleted star, the lower bound is defined by the brightest Li-rich star (excluding J05241914-1601153, which is known to be an unresolved binary and will be brighter than a single star at the same abscissa value – see Table 1). The width of the box is defined by the separation of these two stars, or twice their average uncertainty, whichever is larger.

The LDB age is calculated from the position of the central points of the boxes in Fig. 2 by interpolating the LDB curves. Age uncertainties are estimated by perturbing the abscissae and ordinates according to the height and width of the LDB boxes and adding the resultant age perturbations in quadrature. We also include (in quadrature) an additional ±0.1 mag of uncertainty in colour and magnitude and ±0.5 subclasses in spectral type to reflect likely errors in the calibration of these quantities.

The results are given in the first row of Table 2 for the models of Chabrier & Baraffe (1997). To gain insight into any model dependency we repeated the process using the models of Siess et al. (2000, models with metallicity Z = 0.02) and Burke et al. (2004). Table 2 shows that there is only ~ 2 Myr between the youngest and oldest age estimates from these models (compare the ages in a column). A comparison of the ages in each row shows differences of ≤ 0.6 Myr, attributable to small (0.1 mag) differences in the LDB location in each diagram; the applied bolometric corrections are similar to ≤ 0.04 mag. Finally, we note that defining the LDB as the luminosity at which Li is depleted by 99.9 or 90 per cent would only change the age estimates by ±1 Myr. All these uncertainties are small compared with the 3–4 Myr observational error due to the size of the estimated LDB boxes. Adopting the Chabrier & Baraffe models, our final LDB age estimate is 21 ± 4 Myr, with an additional model dependent uncertainty of only ±1 Myr.

4 DISCUSSION AND IMPLICATIONS

The LDB age derived for the BPMG is reasonable precise, but could be improved by the addition of data for more members close to the LDB and an accurate assessment of their binary nature. More importantly, the LDB method yields an age likely to have a high degree of absolute accuracy. The physics involved in calculating the luminosity at the LDB versus age is well understood. Numerical experiments adjusting the physical inputs of models (convection efficiency, opacities, equation of state etc.) within plausible bounds yield age uncertainties of only 8 per cent at ~ 20 Myr (Burke et al. 2004), comparable with the model dependence we have found.

Previous work on the LDB in the BPMG concluded that the age was > 30 Myr, incompatible with ages derived from fitting isochrones in the HRD or from kinematic traceback, and suggesting there could be gaps in our understanding of the physics of Li depletion (Song et al. 2002; Yee & Jensen 2010). Both of these works suffered from a sparse sample (only the binary pair HIP112312AB was considered by Song et al. 2002); the new BPMG members confirmed here locate the LDB with more precision, particularly in defining the lowest luminosity objects that have lost their Li. However, all the objects considered in previous work are present in Fig. 2 and are entirely consistent with our LDB age. Even if we ignore the new members claimed in this Letter, the presence of previously known Li-depleted objects at $M_K > 5.0$ constrains the LDB age to be > 15 Myr. We think the main reason that previous work found an older age was that comparison was made with Li depletion models as a function of $T_{\text{eff}}$. This is a far more uncertain enterprise than comparing the luminosity of the LDB with models. Measuring $T_{\text{eff}}$ in low-mass stars has systematic uncertainties of 100–200 K at best, leading to large LDB age errors because the Hayashi tracks of stars with different mass are close together in $T_{\text{eff}}$. Furthermore, theoretical $T_{\text{eff}}$ predictions are extremely sensitive to adopted convection efficiencies and atmospheres, making any age estimate highly model-dependent.

The LDB age we find is at the upper end of age estimates from isochronal fits to low mass BPMG members in the HRD – 12–14 Myr (Zuckerman et al. 2001). Isochronal ages are also model dependent, are very sensitive to adopted convective efficiencies, can vary depending on which mass range is considered, may be biased downwards by the neglect of unresolved binarity and also depend on how colours and spectral types are translated into $T_{\text{eff}}$ for comparison with models (or vice versa). The situation is perfectly illustrated in the top panels of Fig. 2, where a single isochrone is incapable of fitting all the low-mass members. Nevertheless, Jefferies et al. 2013 and Bell et al. 2013 have recently shown that for NGC 1960, a rich open cluster with a similar LDB age to the BPMG, that isochronal fits to both low- and high-mass stars do agree with the LDB age when these problems are carefully considered; the same may yet be true for the BPMG.

In principle, kinematic traceback ages provide a model-independent age, or at least the time since the MG occupied a minimum spatial extent. Our LDB age is older than traceback ages of 10–12 Myr reported by Ortega et al. 2002, 2004 and Song et al. 2003, which have formal uncertainties as small as 0.3 Myr. However, other kinematic analyses do not concur with this age or this precision. Torres et al. 2006 find a group expansion consistent with an age of ~ 20 Myr; Makarov (2007) give a time of closest approach for pairs of BPMG members as 22 ± 12 Myr ago; and Mamajek (2013, private communication), using the revised Hipparcos astrometry, was unable to find any significant evidence that BPMG was smaller in the past. The differing conclusions appear to arise from uncertain space motions combined with some subjectivity in which group members are included in the analyses. The forthcoming Gaia astrometry mission may reveal a precise kinematic age for the BPMG, but for now it appears an unreliable technique.

A key role for BPMG members is in testing evolutionary models for low-mass objects and circumstellar material at young ages. Adopting an older age of 21 Myr for the BPMG changes the inferred masses of substellar and planetary companions. Biller et al. 2010 find a faint companion to the BPMG member PZ Tel, estimating a mass for PZ Tel b of 36 $M_{\text{Jup}}$ at an assumed age of 12 Myr. An age of 20 Myr would increase the inferred mass by ~ 30 per cent. Similarly, based on an age of 12±2 Myr, Bonnefoy et al. 2013 estimate a mass of $10^{5.5} M_{\text{Jup}}$ for β Pic b, the uncertainties largely arising from the assumed age. Again, an increase in age to 21 Myr results in a ~ 30 per cent increase in inferred mass,
Table 2. LDB ages for the BPMG. Each column corresponds to a diagram in Fig. 2; each row gives ages based on a different evolutionary model.

| M_K vs V-K | M_K vs J-K | M_K vs SpT |
|------------|------------|------------|
| LDB location | M_K = 5.575 ± 0.385 | M_K = 5.575 ± 0.385 | M_K = 5.575 ± 0.385 |
| V-K = 5.465 ± 0.115 | J-K = 0.885 ± 0.040 | SpT = 4.475 ± 0.525 |
| Mbol | 8.280 ± 0.544 | 8.321 ± 0.556 | 8.307 ± 0.546 |

Ages (Myr)

Chabrier & Baraffe (1997) 20.3 ± 3.7
Siess et al. (2000) 19.9 ± 3.7
Burke et al. (2004) 18.5 ± 3.0

which is however still below the upper limit of 15.5 Ma currently imposed by dynamical constraints (Lagrange et al. 2012).

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