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On the age of the β Pictoris moving group

Eric E. Mamajek★ and Cameron P. M. Bell

Department of Physics & Astronomy, University of Rochester, Rochester, NY 14627, USA

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ABSTRACT

Binks & Jeffries and Malo et al. have recently reported Li depletion boundary (LDB) ages for the β Pictoris moving group (BPMG) which are twice as old as the oft-cited kinematic age of $\sim$12 Myr. In this study, we present (1) a new evaluation of the internal kinematics of the BPMG using the revised *Hipparcos* astrometry and best available published radial velocities, and assess whether a useful kinematic age can be derived, and (2) derive an isochronal age based on the placement of the A-, F-, and G-type stars in the colour–magnitude diagram (CMD). We explore the kinematics of the BPMG looking at velocity trends along Galactic axes, and conducting traceback analyses assuming linear trajectories, epicyclic orbit approximation, and orbit integration using a realistic gravitational potential. None of the methodologies yield a kinematic age with small uncertainties using modern velocity data. Expansion in the Galactic X and Y directions is significant only at the 1.7σ and 2.7σ levels, and together yields an overall kinematic age with a wide range (13–58 Myr; 95 per cent CL). The A-type members are all on the zero-age main sequence, suggestive of an age of $>$20 Myr, and the loci of the CMD positions for the late-F- and G-type pre-main-sequence BPMG members have a median isochronal age of 22 Myr ($\pm$ 3 Myr statistical, $\pm$1 Myr systematic) when considering four sets of modern theoretical isochrones. The results from recent LDB and isochronal age analyses are now in agreement with a median BPMG age of 23 $\pm$ 3 Myr (overall 1σ uncertainty, including $\pm$2 Myr statistical and $\pm$2 Myr systematic uncertainties).

Key words: stars: formation – stars: fundamental parameters – stars: kinematics and dynamics – open clusters and associations: individual: β Pictoris moving group.

1 INTRODUCTION

The β Pictoris moving group (hereafter BPMG) is a kinematic group of dozens of young stars in the solar neighbourhood (Zuckerman & Song 2004; Torres et al. 2008). Such moving groups represent the bridge between the youngest star-forming regions and the older field star population, thereby providing us with crucial snapshots of stellar evolution and physical processes occurring at intermediate ages. The BPMG is unique in its combination of youth and proximity, and these factors have lent it to be one of the few stellar groups where the *Hipparcos* mission (Perryman & ESA 1997) was able to measure precise astrometry for large numbers of individual members. Its close distance and young age also makes the BPMG an ideal candidate for discovering extrasolar planets via direct imaging (e.g. Biller et al. 2013; Males et al. 2014) as well as studying resolved debris discs with high angular resolution observations (e.g. Boccaletti et al. 2009; Churcher, Wyatt & Smith 2011) and identifying substellar companions which offer crucial testbeds for evolutionary models (e.g. Mugrauer et al. 2010; Jenkins et al. 2012). Given the group's importance, it is therefore perturbing that the literature ages for this benchmark population range from $\sim$10–40 Myr. In Table 1, we list the literature age estimates for the BPMG (see also Fernández, Figueras & Torra 2008).

Barrado y Navascués et al. (1999) listed seven systems in the BPMG, and quoted an age of 20 $\pm$ 10 Myr (based on isochronal ages for the pre-main-sequence [pre-MS] M-type stars GJ 799AB and GJ 803). Mamajek & Feigelson (2001) used simple linear trajectories to show that β Pic and the M dwarfs GJ 799AB and GJ 803 may have formed in the vicinity of the Scorpius–Centaurus (Sco–Cen) association $\sim$12 Myr ago. Other nearby young stars showed a similar pattern, with isochronal ages similar to their times of closest pass to Sco–Cen, including the HD 199143 and HD 358623 (BD-17°6128) binary, the V824 Ara (HD 155555) triple system, V343 Nor, and PZ Tel. Zuckerman et al. (2001) provided a list of BPMG members that subsumed only β Pic, GJ 799AB and GJ 803 from the Barrado y Navascués et al. (1999) list, plus the HD 199143, HD 358623, V824 Ara, V343 Nor, and PZ Tel systems mentioned by Mamajek & Feigelson (2001), and a dozen other systems. Zuckerman et al. (2001) estimated an age of 12^{+8}_{-4} Myr based mostly on the position of the stars in the Hertzsprung–Russell (H–R) diagram compared to theoretical isochrones, and a comparison of the Li abundances to those of the TW Hydrae Association (TWA) and Tucana–Horologium (Tuc–Hor) moving group members. Song,

★E-mail: emamajek@pas.rochester.edu

Table 1. Literature age estimates for the BPMG. We adopt the terms 'traceback age' and 'expansion age' generically for any age estimate trying to infer when an unbound group of stars was at its minimum size in the past.

Reference –	Age (Myr)	Method –
Barrado y Navascués et al. (1999)	20 ± 10 Myr	CMD isochronal age (KM stars)
Zuckerman et al. (2001)	12^{+8}_{-4} Myr	H–R diagram isochronal age (GKM stars) + Li depletion
Ortega et al. (2002)	11.5 Myr	Traceback age
Song et al. (2003)	12 Myr	Traceback age
Ortega et al. (2004)	10.8 ± 0.3 Myr	Traceback age
Torres et al. (2006)	∼18 Myr	Expansion age
Makarov (2007)	22 ± 12 Myr	Traceback age
Mentuch et al. (2008)	21 ± 9 Myr	Li depletion
Macdonald & Mullan (2010)	∼40 Myr	Li depletion (magnetoconvection models)
Binks & Jeffries (2014)	21 ± 4 Myr	Li depletion boundary
Malo et al. (2014)	26 ± 3 Myr	Li depletion boundary
Malo et al. (2014)	21.5 ± 6.5 Myr (15–28 Myr)	H–R diagram isochronal age (KM stars)
This work	22 ± 3 Myr	CMD isochronal age (FG stars)
Final	**23 ± 3 Myr (1σ)** **[±2 Myr (statistical), ±2 Myr (systematic)]**	Li depletion boundary and isochronal age (FGKM stars)

Bessell & Zuckerman (2002) found evidence that the Li depletion boundary (LDB) among BPMG members was around spectral type ∼ M4–M4.5 and quoted an upper limit on the group age of <20 Myr. A more recent study by Mentuch et al. (2008) measured Li depletion amongst the Zuckerman & Song (2004) members and derived a model-dependent age of 21 ± 9 Myr through comparison with pre-MS evolutionary models. Yee & Jensen (2010) reanalysed a subset of the Zuckerman et al. (2001) members and compared the ages derived from the H–R diagram and Li depletion. They do not quote an age estimate for the BPMG, but demonstrated that the Li depletion ages were systematically older than the ages derived via the H–R diagram, and attributed this to the discrepancy between the measured M dwarf radii and those predicted by the evolutionary models. Recently, Binks & Jeffries (2014) have confirmed that the LDB is at M4.5 ± 0.5 ($V - K_s \simeq 5.5 \pm 0.1$ mag and $M_{K_s} \simeq 5.6 \pm 0.4$ mag), consistent with an LDB age of 21 ± 4 Myr (statistical) and model-dependent (systematic) uncertainty of only ±1 Myr (as estimated using three sets of evolutionary tracks).

Multiple studies have estimated an expansion age of between 11 and 12 Myr for BPMG. Ortega et al. (2002) traced back the orbits of 19 BPMG systems from Zuckerman et al. (2001) using a realistic Galactic potential, and found that the group was most concentrated within a ∼24 pc wide region 11.5 Myr ago. Ortega et al. (2002) considered their age estimate a 'kinematical age'; however, it is unclear whether this age refers to the minimum mean separation between the individual members, or the girth of the entire group as defined by the most distant members. If it is the latter, then the age is unlikely to be robust as it is subject to the statistical whims of observations or the presence of interlopers. Song, Zuckerman & Bessell (2003) assumed linear trajectories and found that, excepting three outliers, ' all members were confined in a smaller space about ∼12 Mya', where the region encircled in their fig. 4 is about ∼30 pc in diameter. Ortega et al. (2004) conducted another analysis, including the new members from Song et al. (2003), and claim that a group of 14 of the BPMG members reached a minimum size (∼35 pc in radius) 10.8 ± 0.3 Myr ago.

Torres et al. (2006) claim to find evidence of expansion in the BPMG (their fig. 7) and estimate a linear trend of

$$U = 0.053\,\mathrm{km\,s^{-1}\,pc^{-1}}\,(X) - 11\,\mathrm{km\,s^{-1}}, \quad (1)$$

where U is in km s^{-1} and X is in pc. Although they do not cite an expansion age, their slope of 0.053 km s^{-1} pc^{-1} equates to an expansion age of 18 Myr, however no uncertainty is given. Makarov (2007) tracked the times of closest encounter for 14 BPMG members, and concluded that the mean time of nearest approach for those pairs was 22 ± 12 Myr ago (the analysis excluded HIP 29964 and β Pic itself, which was consistently giving minimum separation encounter times with other members of 50–70 Myr ago). Including HIP 29964 and β Pic in his analysis, Makarov (2007) found the mean time of minimum separation to be 31 ± 21 Myr ago. Makarov (2007) concluded that the expansion was weak (∼2–3 km s^{-1}) and that the scatter of encounter times was fairly large. The subsequent kinematic studies by Torres et al. (2006) and Makarov (2007) are suggestive that the 11–12 Myr expansion age quoted by the earlier studies may be irreproducible, or at least depend critically upon which sample of BPMG members are included in the kinematic analysis.

The strength of the conclusions from Ortega et al. (2002), Song et al. (2003), and Ortega et al. (2004) have caused some (e.g. Song, Zuckerman & Bessell 2012) to claim that the expansion age of 12 Myr for BPMG is 'model independent' and therefore more reliable than other age methods. However, this conclusion appears to have ignored the findings of Torres et al. (2006) and Makarov (2007), which are consistent with much slower expansion, and older expansion ages.

The LDB – the luminosity at which Li remains unburned – in the BPMG was recently identified by Binks & Jeffries (2014) who derived an age of 21 ± 4 Myr. More recently, Malo et al. (2014) used the Dartmouth magnetic stellar evolutionary models (see Feiden & Chaboyer 2012, 2013) to derive an average isochronal age of between 15 and 28 Myr and an LDB age of 26 ± 3 Myr using a sample of late K and M dwarfs in the H–R diagram. Although LDB ages are derived using pre-MS evolutionary models, the *luminosity* at which stars in a presumably coeval group transition from those that demonstrate depleted Li to those that do not, is remarkably insensitive to variations in the input physics adopted in the evolutionary models (see e.g. Burke, Pinsonneault & Sills 2004; Jeffries & Oliveira 2005). Given the physically simplistic nature of the models which predict the LDB, in conjunction with the high level of model-insensitivity, Soderblom et al. (2013) describe LDB ages as

Table 2. Positions and velocities of the BPMG stars. Galactic *XYZ* positions and *UVW* velocities are defined as towards the Galactic Centre (*X*, *U*), $\ell = 90°$ (*Y*, *V*), and the North Galactic Pole (*Z*, *W*). Three-dimensional velocities were calculated using kinematic data from the following references (astrometry reference listed first, radial velocity reference listed second). If three references are listed, the source of the parallax is listed first, the source of the proper motion is listed second and the source of the radial velocity is listed third. Positions, spectral types, and *V*-band magnitudes are given in Zuckerman & Song (2004).

Name –	Ref. –	*X* (pc)	*Y* (pc)	*Z* (pc)	*U* (km s^{-1})	*V* (km s^{-1})	*W* (km s^{-1})
HR 9	1,2	4.5	5.9	− 38.7	− 11.0 ± 0.7	− 15.1 ± 1.9	− 10.2 ± 2.9
HIP 10679	1,3,4	− 19.3	13.6	− 13.9	− 10.9 ± 1.9	− 10.8 ± 1.3	− 5.4 ± 0.9
HIP 10680	1,3,2	− 24.3	17.1	− 17.5	− 12.1 ± 1.5	− 14.4 ± 1.1	− 6.8 ± 0.8
HIP 11437B	1,3,5	− 29.4	19.8	− 18.5	− 13.1 ± 1.5	− 14.6 ± 1.2	− 7.8 ± 0.8
HIP 11437	1,3,5	− 29.4	19.8	− 18.5	− 13.5 ± 1.4	− 14.2 ± 1.0	− 8.3 ± 0.6
HIP 12545	1,3,5	− 27.5	7.0	− 31.0	− 10.2 ± 0.8	− 17.7 ± 0.8	− 6.1 ± 0.7
51 Eri	1,6	− 24.0	− 8.1	− 15.0	− 7.2 ± 0.3	− 13.9 ± 0.2	− 5.7 ± 0.1
GJ 3305	1,3,5	− 24.0	− 8.1	− 15.0	− 13.8 ± 0.4	− 16.2 ± 0.3	− 9.6 ± 0.2
HIP 23309	1,3,7	− 1.5	− 21.2	− 16.3	− 11.2 ± 0.3	− 16.6 ± 0.3	− 9.2 ± 0.2
HIP 23418	1,3,2	− 30.9	− 5.7	− 10.8	− 10.1 ± 3.7	− 14.4 ± 3.6	− 9.4 ± 2.5
HIP 35850	1,2	− 20.4	− 13.9	− 11.0	− 12.5 ± 1.1	− 16.8 ± 0.6	− 9.5 ± 0.3
β Pic	1,2	− 3.4	− 16.4	− 9.9	− 11.0 ± 0.5	− 16.0 ± 0.5	− 9.1 ± 0.3
HIP 29964	1,3,8	7.4	− 33.1	− 18.2	− 10.7 ± 0.6	− 16.1 ± 0.6	− 8.2 ± 0.4
HIP 76629	1,2	31.1	− 22.7	− 1.2	− 9.2 ± 0.9	− 17.3 ± 0.8	− 9.8 ± 0.5
HR 6070	1,2	39.0	− 7.9	11.0	− 13.6 ± 0.6	− 16.1 ± 0.4	− 12.3 ± 0.3
HD 155555	1,2	24.7	− 17.4	− 8.8	− 9.5 ± 0.8	− 16.6 ± 1.0	− 8.8 ± 0.6
HIP 88399	1,2	44.3	− 14.7	− 11.6	− 8.0 ± 0.5	− 15.6 ± 0.5	− 9.2 ± 0.3
HR 6749	1,3,2	40.4	− 7.5	− 7.9	− 12.3 ± 0.5	− 15.4 ± 0.4	− 6.9 ± 0.3
HIP 92024	1,2	22.8	− 12.8	− 11.5	− 10.7 ± 2.4	− 15.3 ± 3.0	− 9.0 ± 1.8
CD-64 1208	1,9,7	22.8	− 12.8	− 11.5	− 12.2 ± 1.8	− 16.2 ± 2.1	− 8.6 ± 1.3
PZ Tel	1,3,2	46.8	− 11.5	− 18.2	− 11.7 ± 0.8	− 15.2 ± 0.6	− 8.4 ± 0.4
HR 7329	1,2	41.3	− 12.7	− 21.3	2.1 ± 2.6	− 18.9 ± 2.8	− 14.0 ± 1.8
HIP 95270	1,2,	44.4	− 13.8	− 22.9	− 9.5 ± 0.6	− 16.6 ± 0.5	− 8.6 ± 0.3
GJ 799A	1,10,5	8.5	1.7	− 6.3	− 9.8 ± 0.6	− 16.6 ± 0.5	− 11.1 ± 0.4
GJ 799B	1,10,5	8.5	1.7	− 6.3	− 11.5 ± 0.7	− 18.3 ± 0.6	− 11.5 ± 0.4
GJ 803	1,5	7.7	1.7	− 5.9	− 9.8 ± 0.2	− 16.3 ± 0.1	− 10.7 ± 0.1
HD 199143	1,7	32.3	18.9	− 26.2	− 7.5 ± 1.4	− 13.6 ± 1.1	− 11.2 ± 1.3
BD-17 6128	1,11,7	32.3	18.9	− 26.2	− 9.0 ± 0.8	− 14.2 ± 0.7	− 9.4 ± 0.7
HIP 112312	1,3,5	10.7	2.4	− 20.6	− 11.5 ± 1.6	− 17.9 ± 1.1	− 11.5 ± 0.6
HIP 112312B	1,3,5	10.7	2.4	− 20.6	− 11.2 ± 1.6	− 18.1 ± 1.1	− 10.2 ± 0.6
Mean	–	8.4	− 5.0	− 15.0	− 10.9 ± 0.3	− 16.0 ± 0.3	− 9.2 ± 0.3

References: (1) van Leeuwen (2007), (2) Gontcharov (2006), (3) Zacharias et al. (2012), (4) Nordström et al. (2004), (5) Bailey et al. (2012), (6) Song et al. (2003), (7) Torres et al. (2006), (8) adopted average v_r of Zuckerman et al. (2001) and Torres et al. (2006, 15.7 ± 0.7 km s^{-1}, adopting 1 km s^{-1} error for Torres et al.'s value), (9) Kharchenko & Roeser (2009), (10) Høg et al. (2000), (11) Zacharias et al. (2010).

'semifundamental'. Furthermore, they recommend that LDB ages offer the best hope of establishing a reliable and robust age *scale* for young (< 200 Myr) stellar populations. Thus, it is clear that the revised age of ∼20–25 Myr represents the new 'benchmark' age for the BPMG, against which other age-dating techniques should be validated or tested.

Given the large (factor of ∼2) discrepancy between the LDB and previous kinematic ages, in this contribution we independently re-examine the evidence for kinematic expansion of the BPMG using the best available astrometric data, and conclude whether a unique kinematic age can be assigned to the group. Furthermore, we also investigate age constraints based on the 'turn-on' to the main sequence as observed amongst the A-, F-, and G-type members, and compare these to theoretical model isochrones in colour–magnitude diagrams (CMDs).

2 DATA

2.1 Kinematic data

We use the BPMG membership from Zuckerman & Song (2004) as it defines a sample of 'classic' BPMG members with *Hipparcos* astrometry used in most studies. This sample is more restrictive than the larger sample assembled by Torres et al. (2006, 2008); however, these larger samples contain very few stars with trigonometric parallaxes, and many at larger distances (which increases the chances of interlopers polluting the sample). Ideally, the inclusion or exclusion of a few members should *not* make or break whether a group has a detectable expansion and corresponding age.

Velocities and positions in Galactic Cartesian coordinates were calculated for members of the BPMG using the best available published astrometry and velocities (these are shown in Table 2). All trigonometric parallaxes and celestial positions were taken from the revised *Hipparcos* catalogue of van Leeuwen (2007). Proper motions were usually adopted from van Leeuwen (2007), unless more recent long-term proper motions from the UCAC4 catalogue (Zacharias et al. 2012, which has smaller uncertainties) were available. The majority of radial velocities come from either the compiled catalogue of Gontcharov (2006) or the recent survey of Bailey et al. (2012).

2.2 Photometric data

All the stars in our sample are in the *Hipparcos* catalogue and have Johnson *BV* photometry (either estimated using ground-based observations or from *Hipparcos*). However, no uncertainties are

Table 3. Spectral types, distances and photometry for A-, F-, and G-type members of the BPMG.

Name	SpT	Ref.	V	$B-V$	Ref.	Distance	M_V	Phase
–	–	–	(mag)	(mag)	–	(pc)	(mag)	–
HR 6070	A1Va	1	4.784 ± 0.009	0.016 ± 0.007	9,9	41.29 ± 0.38	1.71 ± 0.05	ZAMS
HR 7329	A0V	1	5.043 ± 0.005	0.020 ± 0.002	9,10	48.22 ± 0.49	1.63 ± 0.05	ZAMS
β Pic	A6V	2	3.845 ± 0.005	0.175 ± 0.005	9,9	19.44 ± 0.05	2.40 ± 0.01	ZAMS
HIP 92024	A7V	2	4.780 ± 0.007	0.197 ± 0.004	9,9	28.55 ± 0.15	2.50 ± 0.03	ZAMS
HR 6749[a]	A6V	3	5.635 ± 0.020	0.222 ± 0.020	11,11	41.84 ± 1.16	2.53 ± 0.14	ZAMS
HR 6750[a]	A7V	3	5.711 ± 0.020	0.234 ± 0.020	11,11	41.84 ± 1.16	2.60 ± 0.14	ZAMS
51 Eri	F0IV	4	5.215 ± 0.009	0.283 ± 0.006	9,9	29.43 ± 0.29	2.87 ± 0.05	ZAMS
HR 9	F3V	5	6.172 ± 0.004	0.386 ± 0.005	9,9	39.39 ± 0.59	3.20 ± 0.08	Pre-MS*
HIP 88399	F4.5V	5	7.007 ± 0.010	0.458 ± 0.015	11,10	48.15 ± 1.30	3.59 ± 0.14	Pre-MS
HIP 99273[b]	F5V	6	7.181 ± 0.010	0.480 ± 0.015	11,10	52.22 ± 1.23	3.59 ± 0.12	Pre-MS
HIP 95270	F6V	5	7.037 ± 0.010	0.480 ± 0.004	11,10	51.81 ± 1.75	3.47 ± 0.17	Pre-MS
HIP 10680[c]	F7V	5	7.031 ± 0.011	0.518 ± 0.021	11,10	37.62 ± 2.73	4.15 ± 0.36	?
HD 199143A[a]	F7V	5	7.323 ± 0.012	0.532 ± 0.016	11,11	45.66 ± 1.61	4.03 ± 0.18	Pre-MS
HIP 25486	F7V	5	6.296 ± 0.010	0.551 ± 0.013	11,11	27.04 ± 0.35	4.14 ± 0.07	Pre-MS
HIP 86598[b]	F9V	7	8.357 ± 0.017	0.558 ± 0.019	11,11	72.46 ± 4.57	4.06 ± 0.32	Pre-MS
HIP 10679[c]	G3V	5	7.755 ± 0.013	0.622 ± 0.008	11,10	37.62 ± 2.73	4.88 ± 0.36	?
HIP 89829[b]	G3IV	5	8.797 ± 0.019	0.639 ± 0.031	11,11	72.57 ± 5.37	4.49 ± 0.37	Pre-MS
HD 155555A[a, d]	G5V	5	7.222 ± 0.100	0.743 ± 0.100	12,10	31.45 ± 0.49	4.73 ± 0.13	Pre-MS
HIP 92680[b]	G9IV	8	8.461 ± 0.014	0.780 ± 0.008	9,9	51.49 ± 2.60	4.90 ± 0.25	Pre-MS

References: (1) Gray & Garrison (1987), (2) Gray et al. (2006), (3) Corbally (1984), (4) Gray (1989), (5) Pecaut & Mamajek (2013), (6) Houk (1982), (7) McCarthy & White (2012), (8) Torres et al. (2006), (9) Mermilliod (1991), (10) Perryman & ESA (1997), (11) Tycho $(BV)_T$ photometry transformed to Johnson BV following Mamajek (2006), (12) Strassmeier & Rice (2000). Distances are based on parallax measurements from the revised *Hipparcos* reduction of van Leeuwen (2007).

Evolutionary phases are based on CMD positions: ZAMS = zero-age main sequence, Pre-MS* = pre-main-sequence phase between penultimate and final (ZAMS) luminosity minima (see Section 4.1), Pre-MS = pre-main sequence.

[a]Individual binary components shown (see Section 4.1 for a description of deconstructing the combined photometric measurements).

[b]Not listed as members in Zuckerman & Song (2004), but identified as bona fide members in Malo et al. (2013).

[c]Due to a large uncertainty in the parallax measurement we instead adopt a kinematic distance (see Section 4.1).

[d]The large uncertainty on both the magnitude and colour is due to the high level of variability associated with the object. We therefore adopt the mean V-band magnitude as given by Strassmeier & Rice (2000) and deconstruct the combined photometry as detailed in Section 4.1.

explicitly given for the Johnson V-band magnitudes. Instead, we adopt BV photometry from the homogenized UBV catalogue of Mermilliod (1991). If homogenized BV data are unavailable, or there are no quoted uncertainties, Tycho-2 $(BV)_T$ photometry (Høg et al. 2000) was instead adopted and transformed to Johnson BV using the conversions presented in Mamajek, Meyer & Liebert (2002, 2006). In addition to the 'classic' Zuckerman & Song (2004) sample of members as discussed in Section 2.1, we also include four stars (HIP 86598, HIP 89829, HIP 92680, and HIP 99273) which are listed as new bona fide members from the study of Malo et al. (2013). Table 3 lists the compiled BV photometry in addition to spectral types and distances for the A-, F-, and G-type BPMG members.

3 KINEMATIC ANALYSIS

The following sections are laid out, in order to test in as simple a way as possible, whether or not it is possible to assign a unique kinematic age to the BPMG. In Section 3.1, we calculate revised basic kinematic parameters for the BPMG (mean velocity and velocity dispersion). In Section 3.2, we calculate the velocity gradients and statistically test whether they are consistent with expansion ages of 11–12 Myr. In Section 3.2.1, we reattempt the analysis of Song et al. (2003) using contemporary kinematic data, following the linear trajectories of the BPMG stars, in search for a signature of an expansion age. In Section 3.2.2, we model the orbits using epicycle approximation, and examine the spatial distribution in the past in search of a unique expansion age.

Astronomical samples often have interlopers, so calculating statistical means, standard errors of means, and standard deviations can often be biased by such interlopers (e.g. Gott et al. 2001). Throughout the kinematic analysis, when we mention a 'mean', we are actually using the average of (1) the median, (2) the Chauvenet clipped mean (Bevington & Robinson 1992), and (3) the probit mean (Lutz & Upgren 1980), i.e. a 'mean' that is remarkably immune to the effects of outliers. When we mention a 'standard error', we are actually using the average of (1) the error of the true median (Gott et al. 2001), and (2) the standard error of the Chauvenet clipped mean (Bevington & Robinson 1992). When we mention 'dispersion', we are quoting the average of (1) the 68 per cent confidence intervals, and (2) the probit standard deviation (Lutz & Upgren 1980). In the limit of a Gaussian distribution lacking outliers, these quantities are asymptotically identical to their normal counterparts: the mean, standard error of the mean, and standard deviation. Our choice of estimators allows one to calculate the statistical moments in a way that is not sensitive to the inclusion or exclusion of some 'problem' stars. Such stars may have been arbitrarily included or excluded in previous studies.

3.1 Revised kinematic parameters for the BPMG

Based on the three-dimensional velocities for the 30 BPMG members in Table 2, we estimate a new mean velocity for the BPMG of

$$U, V, W \; = \; -10.9 \pm 0.3, -16.0 \pm 0.3, -9.2 \pm 0.3 \, \mathrm{km\,s^{-1}} \tag{2}$$

which is in good agreement with the recent estimate of Malo et al. (2014). Here, the Galactic U, V, W velocities are defined in the classic sense, and U is explicitly positive towards the Galactic Centre. This space motion corresponds to an approximate convergent point solution of

$$\alpha_{\mathrm{CP}} \; = 88\overset{\circ}{.}0 \; \pm \; 0\overset{\circ}{.}9 \tag{3}$$

$$\delta_{\mathrm{CP}} \; = -30\overset{\circ}{.}6 \; \pm \; 0\overset{\circ}{.}8 \tag{4}$$

$$S_{\mathrm{tot}} \; = 21.4 \; \pm \; 0.3 \; \mathrm{km\,s^{-1}}. \tag{5}$$

The *observed* 1σ dispersions are σ_U, σ_V, σ_W = 1.8, 1.6, and 1.9 km s^{-1}, respectively. However, to estimate the *intrinsic* one-dimensional velocity dispersion, we need to take into account the mean uncertainties in the individual U, V, W velocities (0.9, 0.9, 0.6 km s^{-1}, respectively). Hence, subtracting off the mean errors in quadrature, we estimate the *intrinsic one-dimensional velocity dispersions* for the BPMG U, V, W velocities to be

$$\sigma_U^{\mathrm{int}}, \sigma_V^{\mathrm{int}}, \sigma_W^{\mathrm{int}} \; = 1.5, 1.4, 1.8 \; \mathrm{km\,s^{-1}}, \tag{6}$$

respectively, i.e. ∼1.5 km s^{-1} in all directions. This is similar to that calculated for the subgroups in the Sco–Cen complex (e.g. de Bruijne, Hoogerwerf & de Zeeuw 2001; Mamajek 2003). The one-dimensional velocity dispersions are somewhat similar to those calculated by Malo et al. (2013) (σ_U^{int}, σ_V^{int}, σ_W^{int} = 2.06, 1.30, and 1.54 km s^{-1}) and Malo et al. (2014) (σ_U^{int}, σ_V^{int}, σ_W^{int} = 2.06, 1.32, and 1.35 km s^{-1}), which used larger samples. However, it is unclear from their text whether the one-dimensional dispersions in Malo et al. (2013) are simply 1σ scatters in the observed velocities (and hence, not intrinsic velocity dispersions) or whether it includes observational uncertainties. The velocity dispersions that we have listed do not take into account any position-dependence of the velocities (which would be a manifestation of expansion, or Galactic differential rotation). This *intrinsic* one-dimensional velocity dispersion should be kept in mind when assigning membership to the BPMG for newly identified young field objects, especially those with heteroskedastic velocity uncertainties.

3.2 Are the velocity trends consistent with expansion?

Using the positions and velocities for the BPMG members compiled in Table 2, we plot the position coordinates *XYZ* versus the velocities along those axes *UVW* in Fig. 1. We use bootstrap sampling of unweighted ordinary least-squares fit to calculate the slopes and slope uncertainties for the *UVW* velocity versus position trends. For the 30 BPMG stars in Table 2, we estimate

$$\kappa_X = \frac{\mathrm{d}U}{\mathrm{d}X} = +0.039 \pm \; 0.024 \, \mathrm{km\,s^{-1}\;pc^{-1}} \tag{7}$$

$$\kappa_Y = \frac{\mathrm{d}V}{\mathrm{d}Y} = +0.052 \pm \; 0.019 \, \mathrm{km\,s^{-1}\;pc^{-1}} \tag{8}$$

$$\kappa_Z = \frac{\mathrm{d}W}{\mathrm{d}Z} = -0.031 \pm \; 0.044 \, \mathrm{km\,s^{-1}\;pc^{-1}}. \tag{9}$$

Both κ_X and κ_Z are within 1.7σ of zero, and κ_Y is only marginally positive (2.7σ). The κ slopes have Pearson r correlation coefficients of 0.35, 0.44, −0.17, and probabilities of zero correlation of 5.6, 1.6, and 35.8 per cent, respectively.

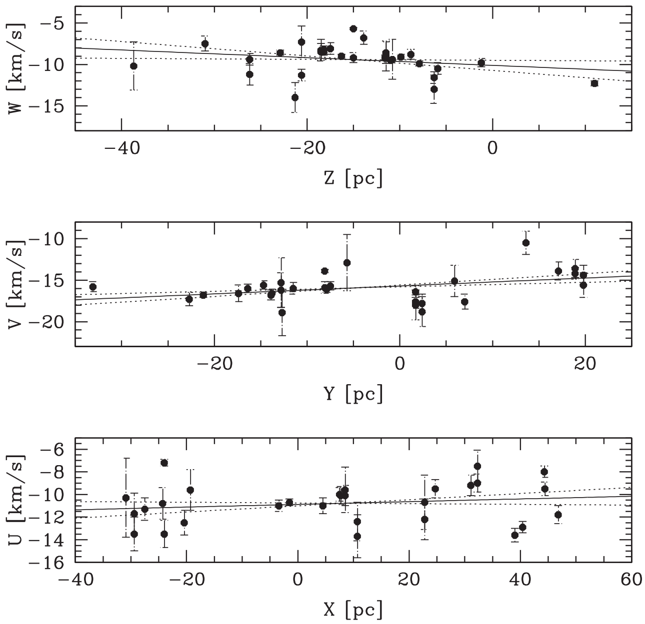

Figure 1. These three panels show position versus velocity along the three Galactic Cartesian axes for the BPMG members from Zuckerman & Song (2004) with measured trigonometric parallaxes. Bottom panel: X versus U (= dX/dt). Middle panel: Y versus V (= dY/dt). Top panel: Z versus W (= dZ/dt).

Expansion time-scales can be calculated using κ following the expression $\kappa = \gamma^{-1}\tau^{-1}$, where γ is the constant 1.022 712 165 s pc km^{-1} Myr^{-1}. It is unclear whether the κ_Z rate is actually useful given that the expected age of the group is not insignificant compared to the vertical oscillation period in the local Galactic disc (∼80 Myr). Given the complication in interpreting the κ_Z value, we omit it from further consideration. The expansion rates κ_X and κ_Y are independently consistent with expansion ages in X and Y of 26 Myr ($^{+41}_{-10}$ 1σ; $^{+86}_{-14}$ 2σ) and 19 Myr ($^{+11}_{-5}$ 1σ; $^{+52}_{-8}$ 2σ), respectively. The weighted mean expansion rate is then $\kappa = 0.047 \; \pm \; 0.015$ km s^{-1} pc^{-1}, which translates to an expansion age of 21 Myr ($^{+10}_{-5}$ 1σ; $^{+38}_{-8}$ 2σ).

The new estimate of κ_X is within the uncertainty of the slope (0.053 km s^{-1} pc^{-1}) measured by Torres et al. (2006). The newly derived κ_X depends on improved astrometry (van Leeuwen 2007) and a larger sample of BPMG stars with trigonometric parallaxes than that used by Torres et al. (2006), so it should be an improved estimate of this velocity trend. If one reverses the problem and *assumes* that the BPMG manifested a linear expansion consistent with an expansion age of 12 Myr, one would expect a slope of $\kappa = 0.081$ km s^{-1} pc^{-1}. This differs from our estimate at the 2.3σ level. Given the slope uncertainties, a linear expansion of the BPMG with time-scale 12 Myr should have been statistically detected at the 5.4σ and 3.9σ level in X and Y, respectively, however it clearly was not. Hence, the velocity trends are inconsistent with expansion on a 12 Myr time-scale. This methodology hints that the group may have been somewhat more compact in the past, however the 95 per cent confidence range of expansion age (13–59 Myr), and the fact that the expansion in X and Y together is only ∼3.1σ away from zero, suggests that this sort of methodology will not provide an accurate or useful kinematic age with the available astrometry.

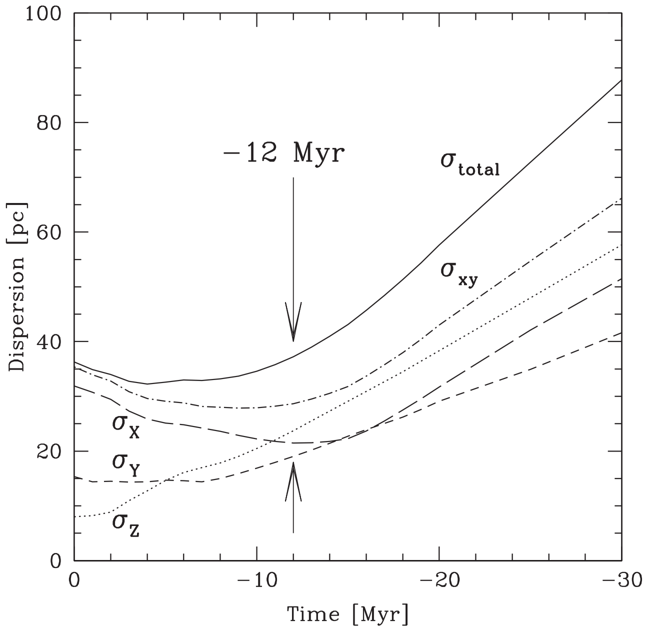

Figure 2. 1σ dispersions in X, Y, Z coordinates (σ_X, σ_Y, σ_Z) as a function of time in the past, assuming linear trajectories. The quadrature sums of the X and Y dispersions (σ_{XY}) and X, Y, and Z dispersions ($\sigma_{\rm total}$) are also plotted. Linear trajectories in Z are obviously the poorest approximation (contrast with dispersion measured for epicyclic orbit in Fig. 4). The σ_{XY} dispersion may be the most useful overall metric of the group's size using the linear trajectory technique.

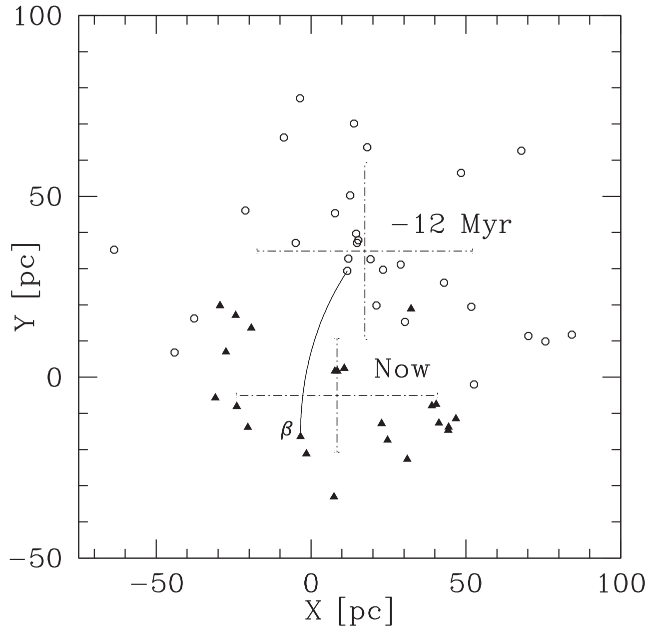

Figure 3. Distribution of BPMG members in the XY plane now (filled triangles) and 12 Myr ago (open circles) using epicycle orbit approximation. The dispersion in the X and Y directions are plotted now and 12 Myr ago. The trajectory for the star β Pic itself is plotted as a solid arc, and labelled with a 'β'. The reference frame has its origin at the Sun's current position, but is comoving with the LSR of Schönrich et al. (2010).

3.2.1 *Simple linear trajectories*

Following Song et al. (2003), we calculate linear trajectories for the revised positions and velocities for BPMG members in Table 2 using

$$X(t) = X_\circ + \gamma U t \tag{10}$$

$$Y(t) = Y_\circ + \gamma V t \tag{11}$$

$$Z(t) = Z_\circ + \gamma W t, \tag{12}$$

where subscript $_\bigcirc$ denotes the present positions, t is time in Myr (negative for the past), *XYZUVW* carry the usual definitions, and γ is the constant 1.022 712 165 s pc km^{-1} Myr^{-1}. Fig. 2 shows the 1σ dispersions in X, Y, Z from the present to 30 Myr ago. The dispersion in Z steadily increases as one goes further in the past. The dispersion in Y has been fairly steady over the past 10 Myr, but steadily increases as one goes further back. The dispersion in X decreases slightly as one goes back, bottoming out at around 12 Myr ago; however, the X dispersion varied little (<5 per cent) between 9 and 15 Myr ago. The minima in the dispersion in X, Y, Z, X & Y, and XYZ, occurred at times of 12, 3, 0, 9, and 6 Myr ago, respectively. The minimum for the Z dispersion at present is unsurprising given how poor the approximation of a linear trajectory is in the Z direction (i.e. epicyclic period in Z is shortest among the three directions). Arguably the most useful dispersion to look at for the linear trajectory approximation is the quadrature sum of X and Y; however, this shows a very broad minimum which changed at the <5 per cent level between ~5 and ~12 Myr ago. We conclude that using the linear trajectory approximation and defining the size of the group in terms of their 1σ dispersions does not lead to an unambiguous kinematic age for the BPMG using the currently available astrometry.

3.2.2 *Epicycle orbit approximation*

For the epicyclic approximation, we use the orbit equations from Fuchs et al. (2006), and adopt Oort A and B constants from Feast & Whitelock (1997), the local disc density from van Leeuwen (2007), the local standard of rest velocity from Schönrich, Binney & Dehnen (2010), and a solar Z distance above the Galactic plane of 20 pc. In Fig. 3, we show the XY positions for the BPMG members from Zuckerman & Song (2004) now and at 12 Myr ago. The current distribution of BPMG members is very irregular, with no real concentration. It appears that 12 Myr ago, there were a few more stars near the centroid of the group, but surprisingly the dispersion in the positions was somewhat *larger* than measured for the present. Note that the dispersions are measured using the average of the 68 per cent confidence intervals and probit estimate of the standard deviation, hence they are extremely resilient to the effects of outliers.

In Fig. 4, we plot the dispersions in the X, Y, Z directions (σ_X, σ_Y, σ_Z) as a function of time in the past for the BPMG sample. We also plot the square root of the sum of these dispersions added in quadrature ($\sigma_{\rm total}$) as a simple metric of the overall positional dispersion. The dispersion in the X direction was marginally smaller ~5 Myr ago, but grows monotonically further back in time (as does the dispersion in Y). The local minimum at 5 Myr ago cannot be taken seriously as an expansion age as the velocity trends calculated in Section 3.2 are all clearly inconsistent with such a rapid expansion (5 Myr → κ = 0.20 km s^{-1} pc^{-1}). The dispersion in Z is only ±8 pc now, but was ±20 pc 12 Myr ago. Surprisingly, we find that the size of the group, as measured by a statistical estimate of the dispersion, was somewhat *larger* 12 Myr ago, at odds with the claims of Ortega et al. (2002) and Song et al. (2003). As can be seen in Fig. 4, the positional dispersion along the three axes for the BPMG stars 12 Myr ago was similar to, or somewhat larger than, the currently measured dispersion. Again, the evidence is lacking for a

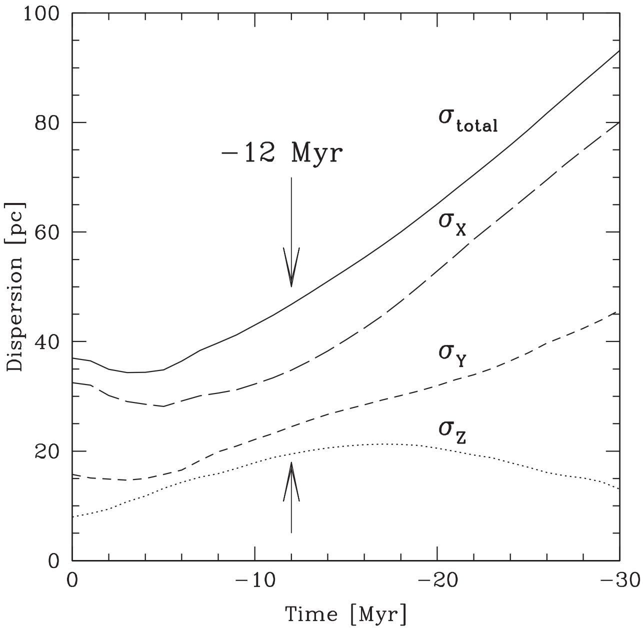

Figure 4. Current and past dispersions in the Galactic *X*, *Y*, and *Z* positions for the 30 BPMG stars from Zuckerman & Song (2004), with the same axes and scale as Fig. 2. Orbits were traced back using an epicycle code, and the dispersions are an average of the 68 per cent confidence intervals and probit estimate of σ (i.e. an estimate of the standard deviation immune to outliers). No unambiguous minimum in the dispersions is visible at the oft-cited age of 12 Myr.

more compact configuration for the BPMG 11–12 Myr ago, or for assigning any unambiguous expansion age.

3.2.3 *NEMO orbit integration*

To determine whether a lack of unambiguous expansion age is the result of our choice of epicycle code, we also study the past orbits of the BPMG members using the NEMO stellar dynamics code (Teuben 1995), for which we adopt the Galactic potential (model 2) of Dehnen & Binney (1998). Fig. 5 shows the dispersions in the *X*, *Y*, *Z* directions as a function of time (also listed in Table 4). While there is a minimum in *X* positions at ∼12 Myr ago, the BPMG was larger in both *Y* and *Z* during that epoch. Using the most realistic orbit approximation of the three tried, we see that the overall dispersion in *X*, *Y*, and *Z* has a broad minimum at between ∼3 and ∼12 Myr ago, but there does not appear to be unambiguous evidence of a well-defined minimum which could provide a useful kinematic age.

3.3 Discussion on kinematic ages

An age based on the expansion of the BPMG would only be useful if its uncertainty were much less than the actual age. Based on our analysis, it is difficult to see how an expansion age with small uncertainties can be inferred from the currently available kinematic data. While the velocity trends in Galactic *X* and *Y* directions are consistent with an expansion age of 21^{+10}_{-5} Myr (1σ), when the past orbits of the BPMG were examined using epicyclic orbit approximation, and orbit integration using a realistic Galactic potential, a well-defined expansion age is not apparent. We conclude that using the current astrometric data, we can-not assign a unique, precise expansion age.

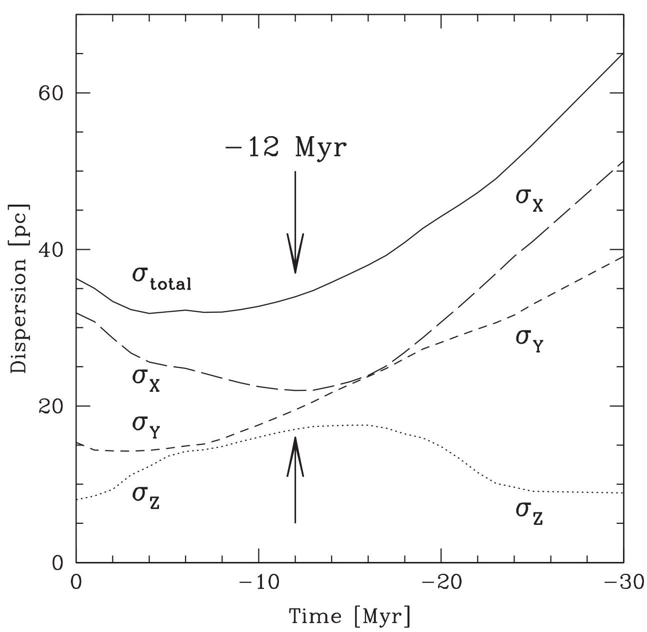

Figure 5. Same as Fig. 4 but with the orbits integrated using the NEMO dynamics code. A minimum in the dispersions is not visible at the classic age of 12 Myr.

Table 4. Dispersion in positions of BPMG members now and in the past using the NEMO stellar dynamics code.

Time (Myr)	σ_X (pc)	σ_Y (pc)	σ_Z (pc)
0	31.9	15.4	8.0
−5	25.1	14.6	13.6
−10	22.5	17.6	16.0
−12	22.0	19.5	17.0
−15	23.1	22.7	17.5
−20	30.7	28.1	14.8
−25	41.0	33.0	9.1
−30	51.3	39.1	8.9

To infer a systematic expansion age of 11–12 Myr for the BPMG, one would probably have to choose and omit particular objects (as did Song et al. 2003); however, this would either negate the reliability of determining a global expansion rate for the whole group, or force one to significantly cut down on the number of BPMG bona fide members (which there seems to be little astrophysical motivation for doing). Indeed, the trend in the literature has been to add more and more members to the BPMG, despite the fact that it appears that the group was not significantly much more compact in the past.

4 ISOCHRONAL AGE FROM THE MAIN-SEQUENCE 'TURN-ON'

Having demonstrated that attributing an unambiguous kinematic age of ∼12 Myr to the BPMG is not supported by current kinematic evidence, we now move on to discussing age constraints from the main-sequence 'turn-on' and comparing the positions of stars in the CMD to theoretical model isochrones.

For this comparison, we will concentrate solely on the intermediate-mass A-, F-, and G-type BPMG members, which are likely to either be on the zero-age main sequence (ZAMS) or in the pre-MS phase. We focus on the intermediate-mass stars as evolutionary models predict multiple maxima/minima in the luminosities of the stars as they approach the ZAMS (e.g. Iben 1965), resulting in inflection points in the model isochrones which should be discernible with precise data.

4.1 CMD and pre-MS isochronal age

As discussed in Section 2.2, we have compiled Johnson *BV* photometry for all the A-, F-, and G-type BPMG members and can therefore compare their positions in CMDs to theoretical model isochrones. The reason we compare the models and the data in the M_V, $B-V$ CMD is that reliable *BV* photometry is available for all of the stars, whereas reliable magnitudes in other common optical-IR bands [e.g. $(RI)_{\rm c}JHK_{\rm s}$] are only available for some. Positions in the CMD, however, can be compromised by the effects of unresolved multiplicity on colours and magnitudes, as well as poor distances.

Some of the systems are known to be binaries which may have been resolved in one photometric band, but not in the catalogue providing the *BV* photometry. There are three unresolved binary systems in our sample of A-, F-, and G-type members: HR 6749+HR 6750 (A5V+A5V), HD 199143AB (F7V+M2V), and HD 155555AB (G5V+K0V), all of which have separations of less than 2 arcsec. Plotting the combined photometry for each binary would bias the ages inferred from the CMD and so we deconstruct the combined photometric measurements into individual component measurements. We calculate the individual component colours and magnitudes for these systems following the technique of Mermilliod et al. (1992), using the unresolved *V*-band magnitude, $B-V$ colour, and ΔV-band magnitude between the two components.

Of the stars in our sample, both HIP 10679 and HIP 10680 (which together form a G3V+F7V binary with a separation of 14 arcsec) have sufficiently large uncertainties in the measured parallaxes ($\varpi = 36.58 \pm 5.83$ and 28.97 ± 2.88 mas for HIP 10679 and 10680, respectively; van Leeuwen 2007) to warrant calculating kinematic parallaxes. We therefore adopt the mean of the UCAC4 proper motions for both components, and use the convergent point solution derived in Section 3.1 to calculate a revised kinematic parallax for both HIP 10679 and HIP 10680 of $\varpi = 26.58 \pm 1.93$ mas. We adopt this revised kinematic parallax as opposed to the distance based on the revised *Hipparcos* reduction.

To derive the necessary bolometric corrections and colour–$T_{\rm eff}$ relations to transform the model isochrones from H–R diagram to CMD space we followed the formalism of Girardi et al. (2002) and calculated synthetic bolometric corrections BC_{R_λ} in a given bandpass with response function R_λ as

$$\mathrm{BC}_{R_\lambda} = \mathrm{M}_{\mathrm{bol},\odot} - 2.5\log\left(\frac{4\pi(10\mathrm{pc})^2 F_{\rm bol}}{\mathrm{L}_\odot}\right) + 2.5\log\left(\frac{\int_\lambda \lambda F_\lambda 10^{-0.4A_\lambda} R_\lambda\,\mathrm{d}\lambda}{\int_\lambda \lambda f^\circ_\lambda R_\lambda\,\mathrm{d}\lambda}\right) - m^\circ_{R_\lambda}. \quad (13)$$

Here, $F_{\rm bol} = \sigma T_{\rm eff}^4$ is the total flux emergent at the stellar surface, F_λ is the flux at the stellar surface and A_λ is the extinction in the bandpass. We note that all the BPMG members in this study lie within a distance of 75 pc and are therefore subject to negligible reddening (see discussion in Pecaut & Mamajek 2013), hence we adopt $A_\lambda = 0$. For the response functions R_λ, we adopt the revised *BV* bandpasses from Bessell & Murphy (2012). The term f°_λ denotes a reference flux which produces a known apparent magnitude m°_λ. To ensure that the model isochrones are as close to the standard Johnson *BV* system as possible, we adopt the CALSPEC alpha_lyr_stis_005[1] Vega spectrum as well as the zero-point (and additional zero-point) offsets as described in Bessell & Murphy (2012). Finally, we adopt the revised solar parameters from Mamajek (2012) which take into account recent total solar irradiance measurements from Kopp & Lean (2011): $M_{\mathrm{bol},\odot} = 4.755$ mag and $\mathrm{L}_\odot = 3.827 \times 10^{33}$ erg s^{-1}.

Fig. 6 shows the M_V, $B-V$ CMDs for the A-, F-, and G-type BPMG members with the Yonsei–Yale (Y^2; Demarque et al. 2004), Dartmouth (Dotter et al. 2008), Pisa (Tognelli, Prada Moroni & Degl'Innocenti 2011) and PARSEC (Bressan et al. 2012) model isochrones overlaid. The isochrones have been transformed into the observational plane using the ATLAS9 atmospheric models of Castelli & Kurucz (2004), for which we assume no α-element enhancement.

Despite the differences in the underlying assumptions adopted in the evolutionary models (e.g. protosolar composition, convection, etc.), it is clear that the 'classic' group age of 12 Myr is not supported by comparison of the CMD positions to any of the model isochrones. The A-type stars (HR 6070, HR 7329, β Pic, HIP 92024, HR 6749, and HR 6750) and the F0 star 51 Eri are on the ZAMS (indeed, 51 Eri essentially defines the main-sequence 'turn-on'). All four sets of model isochrones do an admirable job of tracing the ZAMS for the A1–F0 stars, i.e. the stars between ~1.6–2.1 M$_\odot$ have passed the final luminosity and radius minimum of their contraction, and are now stably CNO-burning on the main sequence. If the group were 12 Myr old, all four sets of model isochrones would predict that only the two hottest A0/A1-type stars (HR 6070 and HR 7329) would be on or near the ZAMS, whereas all the cooler stars (including β Pic itself!) should be pre-MS, however this is clearly not the case.

The F3V star HR 9 ($B-V = 0.39$ mag, $M_V = 3.20$ mag) appears to be in a region of the CMD between where the model isochrones predict a second (penultimate) luminosity minima and the final luminosity minimum corresponding to the ZAMS (where the first luminosity minima occurs at the transition between the star being mostly convective [Hayashi phase] and mostly radiative [Henyey phase]). Evolutionary models predict that stars more massive than about 1.2 M$_\odot$ first contract to a ^{12}C(p,γ)-burning sequence – essentially a '*false ZAMS*' – before reaching the full CNO-burning ZAMS. After the core ^{12}C is depleted to equilibrium levels with ^{14}N via the CN (Bethe–Weizsäcker) cycle, the core contracts further and the temperature increases until the rest of the CNO-I cycle can complete and ^{12}C transitions from a consumed fuel to a catalyst, and ^{12}C returns to equilibrium levels [via ^{14}N(p,γ)^{15}O($\beta^+\nu$)^{15}N and (p,α)^{12}C reactions; Iben 1965; Clayton 1983]. Using the example of the star HR 9 (a ~1.5 M$_\odot$ star), the MESA stellar evolution code (Paxton et al. 2011) predicts that a star of this mass with protosolar initial composition takes ~13 Myr of pre-MS evolution to contract to the penultimate luminosity minimum ('false ZAMS'), and another ~10 Myr to reach the final CNO-burning ZAMS at an age of ~23 Myr. Although the luminosity minima differ by only ~0.04 dex in log(L/L$_\odot$), the evolution from the 'false ZAMS' (penultimate pre-MS luminosity minimum) to the ZAMS (final luminosity minimum) takes nearly as long as the pre-MS contraction phase to the 'false ZAMS'. This stage is often ignored in the literature on the evolution of young stars, but it can correspond to a sizeable fraction of the early lifespan of a young massive (>1.2 M$_\odot$) star. HR 9 may hence be an example of a star in this phase where incomplete

[1] http://www.stsci.edu/hst/observatory/cdbs/calspec.html

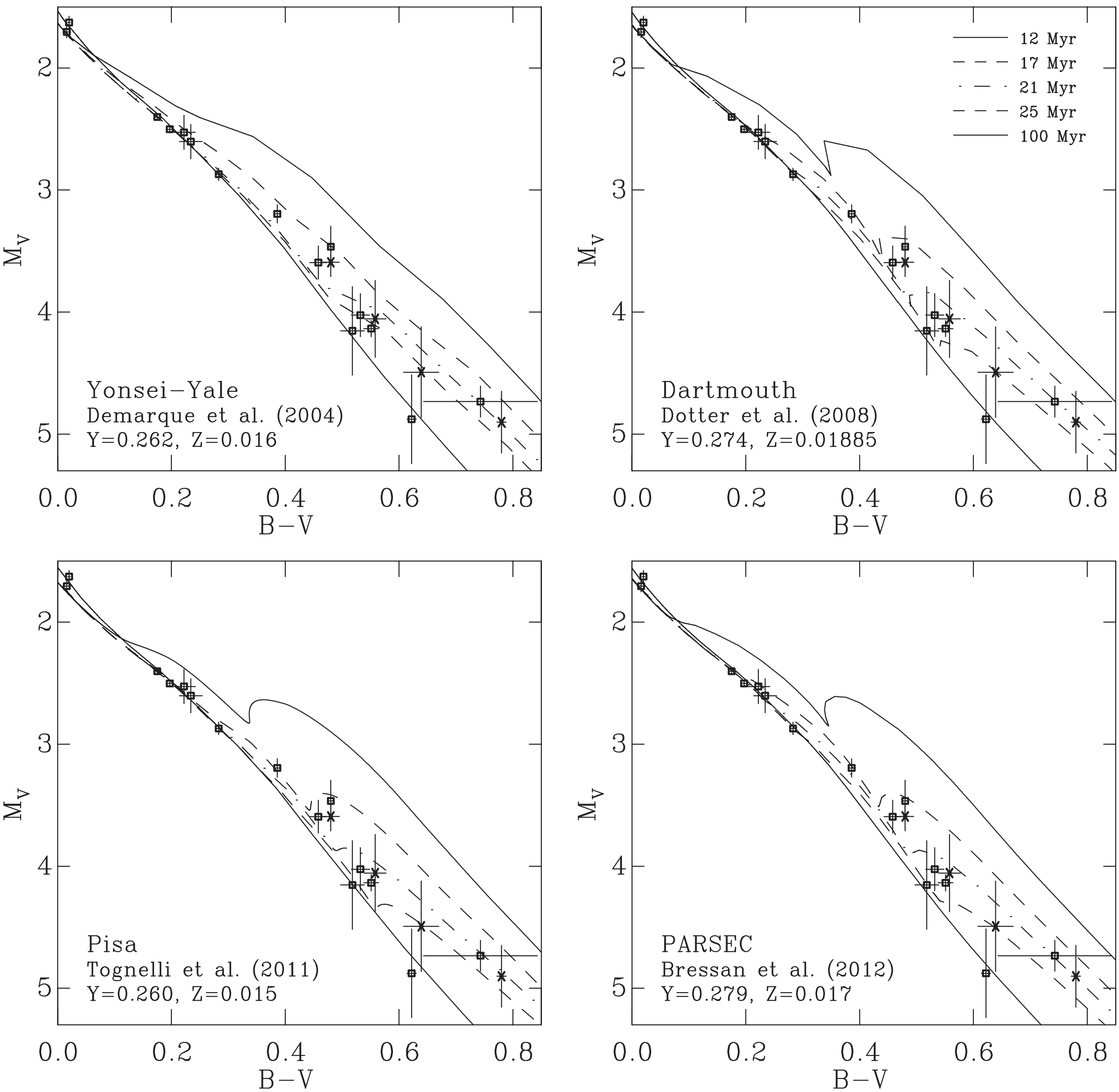

Figure 6. M_V, $B-V$ CMDs of the A-, F-, and G-type BPMG members compared against the Yonsei–Yale (Y^2; Demarque et al. 2004, top left), Dartmouth (Dotter et al. 2008, top right), Pisa (Tognelli et al. 2011, bottom left) and PARSEC (Bressan et al. 2012, bottom right) model isochrones. In all panels the upper continuous line represents the position of the single-star sequence for the oft-quoted age of 12 Myr. Below this, the dot–dashed and bounding dashed isochrones represent the position based on the LDB age of 21 ± 4 Myr according to Binks & Jeffries (2014). Finally, the lower continuous line denotes the position for an age of 100 Myr. The squares represent the 'classic' sample of members as defined by Zuckerman & Song (2004) whereas the crosses denote additional members from Malo et al. (2013).

nuclear CNO cycle burning has initiated; however, core temperatures have not yet reached the point where the full CNO cycle operates catalytically and halts the star's contraction. The stars cooler than HR 9 (type F4 and later) are overluminous compared to both the ZAMS and 'false ZAMS', and seem to be pre-MS stars (see Fig. 6; exceptions are HIP 10679 and HIP 10680 which have particularly large parallax errors).

We can calculate an isochronal age for the BPMG using the F- and G-type stars which are still in the pre-MS phase and estimate an age for each star by linearly interpolating between finely spaced grids of model isochrones. Table 5 shows the median age estimates for the BPMG from the four sets of model isochrones adopted in this study. We derive ages (rounded to the nearest 1 Myr) for both (1) the 'classic' sample of members as defined by Zuckerman & Song (2004) and (2) the combined sample which includes additional members from Malo et al. (2013); however, we note that both ages are statistically indistinguishable. We exclude HIP 10679 and HIP 10680 from the analysis due to their large absolute magnitude uncertainties and the fact that their CMD positions near or below the ZAMS preclude a useful assessment of their isochronal ages

Table 5. Median age estimates for the pre-MS F- and G-type BPMG members using both the 'classic' membership from Zuckerman & Song (2004) and the combined sample which includes additional members from Malo et al. (2013).

BPMG sample	Median age (Myr)			
	Yonsei–Yale	Dartmouth	Pisa	PARSEC
Zuckerman & Song (2004)	20 ± 3	21 ± 3	20 ± 3	21 ± 2
Zuckerman & Song (2004) + Malo et al. (2013)	21 ± 4	22 ± 3	22 ± 2	21 ± 3
F- and G-type isochronal age	22 Myr (±3 Myr statistical, ±1 Myr systematic)			

(see Fig. 6). Using the isochrones, we estimate the BPMG age to be 22 ± 3 Myr, where the uncertainty is dominated by ±3 Myr statistical uncertainty, with a minor systematic uncertainty of ±1 Myr reflecting minor differences between the isochrones.

4.2 Comparison to other age estimates and adoption of a final age

While our new isochronal age for the F- and G-type pre-MS members of BPMG (22 ± 3 Myr) is nearly twice as old as the classic BPMG age of ∼12 Myr, it compares favourably with the recent LDB age estimates by Binks & Jeffries (2014) and Malo et al. (2014, 21 ± 4 Myr and 26 ± 3 Myr, respectively). It is also commensurate with the revised isochronal age from Malo et al. (2014, 15–28 Myr) for the K- and M-type pre-MS members using evolutionary tracks which include a magnetic field model. Our new isochronal age estimate is also in line with other recent estimates based on Li depletion (21 ± 9 Myr; Mentuch et al. 2008) and more recent kinematic estimates (Torres et al. 2006; Makarov 2007). Indeed, *none* of the studies over the past decade using a variety of methods has estimated an age as low as the kinematic ages of ∼11–12 Myr reported by Ortega et al. (2002, 2004) and Song et al. (2003). As we concluded previously, it is not clear that a unique kinematic age with small uncertainties can be quoted. However, taking into account the recent LDB analyses by Binks & Jeffries (2014) and Malo et al. (2014), as well as the recent isochronal age analyses for the K and M stars by Malo et al. (2014) and the F and G stars by this study, a median BPMG age of 23 ± 3 Myr (±2 Myr statistical, ±2 Myr systematic) seems to adequately fit the positions of the stars in both the H–R diagram and CMD as well as the Li depletion pattern of the A- through M-type group members.

Whilst we have used contemporary sets of pre-MS evolutionary models to derive an isochronal age, these models still neglect certain physical phenomena such as the effects of stellar rotation and magnetic fields. Recently, Malo et al. (2014) used the Dartmouth magnetic stellar evolutionary models to derive an average isochronal age of between 15 and 28 Myr for the BPMG K- and M-type stars as well as an LDB age of 26 ± 3 Myr. This study reported significant differences in the luminosity (at a given effective temperature) between models which include a magnetic field and those that do not, in the sense that models with appreciable magnetic field strengths are more luminous (e.g. $\Delta L_{\rm bol} \simeq 0.3$ dex for $B_{\rm surf} = 2.5$ kG). Unfortunately, these magnetic evolutionary models are currently unavailable for the spectral types we are concerned with in this study, however work on a full grid is underway (Fieden, private communication). Thus, at present we are unable to provide a quantitative assessment of the effects of such models on an isochronal age based on the F- and G-type BPMG members, although a qualitative discussion is possible.

Literature measurements for surface magnetic fields on pre-MS F- and G-type stars are extremely sparse and suggest field strengths of less than 1 kG (see e.g. Reiners 2012). Fig. 4 of Malo et al. (2014) compares the position in the H–R diagram of magnetic and non-magnetic evolutionary models, and from this it appears as though there is a maximum difference of $\Delta L_{\rm bol} \lesssim 0.1$ dex for a 1 kG model at effective temperatures less than 3800 K. It is unclear whether such a difference in luminosity remains constant through the G- and into the F-type regime (which seems unlikely given the large difference in the depth of the convective zone across such spectral types); however, if we assume a conservative and constant upper limit of 0.1 dex, then this equates to ≃0.25 mag difference in the absolute bolometric magnitude. Such a difference in the absolute magnitude would imply that the BPMG has an age of ≃ 30 Myr based on the contraction of the F- and G-type members. Given that this 'possible' age is consistent with the upper limit of the Malo et al. (2014) age, it will therefore be interesting to see whether, when the grid of magnetic evolutionary models is complete, consistency between the isochronal ages of the F-, G-, K-, and M-type stars (in addition to the LDB age) is found. Furthermore, given that the adopted magnetic field strength in the evolutionary models can have a significant effect on the model isochrone – and hence isochronal age – it is crucial to have some constraints on which value should be applied to the models and over which spectral type range. Hence calculating the field strength for a number of BPMG members would be extremely beneficial for constraining what is essentially a free parameter.

5 CONCLUSIONS

Analysis of the kinematics of the BPMG, as well as isochronal age constraints based on the main-sequence 'turn-on' and pre-MS F- and G-type stars, yields the following findings.

(i) The trends in Galactic velocity versus position for the BPMG members show only marginal evidence for expansion with the best available velocity data. The most significant velocity trend detected is velocity trend of V as a function of Y ($dV/dY = 0.052 \pm 0.019$ km s^{-1} pc^{-1}), which is only significant at 2.7σ. Combining the expansion rates in X and Y, one can derive a low accuracy expansion age of 21^{+10}_{-5} Myr (1σ uncertainty; however the 2σ range spans 13–59 Myr). Hence, while the velocity trends are at least consistent with an expansion age of ∼20 Myr, the uncertainties remain large using revised *Hipparcos* astrometry and modern radial velocity estimates.

(ii) Integrating the orbits of the BPMG using a realistic Galactic potential, and tracing their orbits back in time shows that the size of the BPMG does not appear to have been significantly smaller in the past. At 12 Myr ago, the dispersion in X positions was smaller than the current value, but the dispersions in both the Y and Z positions were larger. At this point we are not comfortable assigning a unique and useful traceback age for the BPMG.

(iii) The CMD positions for the A-, F-, and G-type members of the BPMG appear to be consistent with an age almost twice as old as the classic age of 12 Myr. The appearance of the A0–F0 stars on/near the ZAMS (including β Pic itself) is consistent with isochronal ages of >20 Myr. The locus of members in the spectral type range F3–G9 are consistent with a pre-MS isochronal age of 22 $\pm$ 3 (statistical) $\pm$ 1 (systematic) Myr, where the systematic uncertainty takes into account the scatter in inferred ages from examining four sets of published theoretical model isochrones.

(iv) The CMD positions of the BPMG stars, as well as their pattern of Li depletion, appear to be consistent with a median consensus age of 23 $\pm$ 3 Myr. This age is commensurate with (1) the appearance of the BPMG A-type members on the ZAMS (this study), (2) the CMD positions for the F- and G-type BPMG members compared to theoretical model isochrones (this study), (3) the isochronal ages for the pre-MS K- and M-type stars when including a treatment for magnetic fields (Malo et al. 2014), and (4) the LDB (Binks & Jeffries 2014; Malo et al. 2014). The age is also consistent with other recent estimates based on Li depletion (Mentuch et al. 2008), as well as kinematic analyses (Torres et al. 2006; Makarov 2007), whose imprecise kinematic ages are at least consistent more with ~20 Myr than ~12 Myr. At this point, we are unable to reconcile these results with the older Li depletion age (~40 Myr) estimated by Macdonald & Mullan (2010) using magnetoconvection models.

Song et al. (2012) recently advocated adopting an expansion age estimate of 12 Myr for the BPMG as a 'model-independent age' for this important young stellar group. Based on the results shown here we would recommend against adopting *any* of the previously published expansion ages for the BPMG, and disregard any conclusions regarding the reliability of *other* age indicators based on comparison to kinematic ages for the BPMG (see also recent review by Soderblom et al. 2013). In particular, the conclusions by Song et al. (2012) that the mean ages of the Lower Centaurus–Crux (LCC) and Upper Centaurus–Lupus (UCL) subgroups of Sco–Cen are ~10 Myr are rendered invalid as their group ages were assessed through comparison to kinematic ages for both the BPMG and the TWA. The Li depletion pattern for low-mass members of LCC and UCL hint that it is intermediate in age between the BPMG and TWA. However, mean isochronal ages for LCC and UCL of 16–17 Myr have been independently assessed for both the B-type main-sequence 'turn-off' members (Mamajek et al. 2002) and F-type pre-MS members (Pecaut, Mamajek & Bubar 2012). The mean LCC and UCL ages estimated by Mamajek et al. (2002) and Pecaut et al. (2012) are consistent with the Li depletion pattern observed by Song et al. (2012) if indeed BPMG is ~23 Myr and TWA is ~8–10 Myr (Weinberger, Anglada-Escudé & Boss 2013; Ducourant et al. 2014).

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