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Bayesian assessment of moving group membership: importance of models and prior knowledge

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ABSTRACT

Young nearby moving groups are important and useful in many fields of astronomy such as studying exoplanets, low-mass stars, and the stellar evolution of the early planetary systems over tens of millions of years, which has led to intensive searches for their members. Identification of members depends on the used models sensitively; therefore, careful examination of the models is required. In this study, we investigate the effects of the models used in moving group membership calculations based on a Bayesian framework (e.g. BANYAN II) focusing on the beta-Pictoris moving group (BPMG). Three improvements for building models are suggested: (1) updating a list of accepted members by re-assessing memberships in terms of position, motion, and age, (2) investigating member distribution functions in *XYZ*, and (3) exploring field star distribution functions in *XYZ* and *UVW*. The effect of each change is investigated, and we suggest using all of these improvements simultaneously in future membership probability calculations. Using this improved MG membership calculation and the careful examination of the age, 57 bona fide members of BPMG are confirmed including 12 new members. We additionally suggest 17 highly probable members.

Key words: methods: statistical – stars: kinematics and dynamics – open clusters and associations: general – open clusters and associations: individual: β-Pictoris moving group.

1 INTRODUCTION

Young nearby moving groups (MGs hereafter) are sparse stellar associations whose members were formed together in loose environment and share common proper motions. Therefore, members of MGs spread out over time in space, and, after hundreds of millions of years, they are not easily distinguishable against old field stars. After the first identification of the nearby young MG, TW Hydrae Association (Kastner et al. 1997), about 10 additional MGs were identified (Webb et al. 1999; Torres et al. 2000, 2008; Zuckerman & Webb 2000; Zuckerman et al. 2001b, 2011; Zuckerman & Song 2004).

Nearby young MGs are unique objects in astronomy because of their proximity and youth. MG members are prime targets for exoplanet imaging (Chauvin et al. 2004; Marois et al. 2008; Lagrange et al. 2010), because orbiting young planets are brighter and more widely separated compared to those around old, distant stars. They are also useful in calibrating stellar age-dating methods and in studying the evolution of low-mass stars (Malo et al. 2014; Murphy, Lawson & Bento 2015; Bink & Jeffries 2016). In addition, they are essential to understanding the recent star formation history in the solar neighbourhood (Torres et al. 2003; Schneider et al. 2012). These studies are critically dependent on assignments of MG membership because they rely on MG group properties such as age, space motion, and location from Earth that are derived from known MG members.

Because of their importance, identification of MG members has been intensively investigated (Song, Zuckerman & Bessell 2003; Zuckerman & Song 2004; Torres et al. 2006; Schlieder, Lépine & Simon 2010; Kiss et al. 2011; Rodriguez et al. 2011; Shkolnik et al. 2012; Malo et al. 2013; Gagné et al. 2014; Murphy et al. 2015). Among methods applied to searching for MG members, a statistical approach based on a Bayesian framework has become popular recently (Malo et al. 2013; Gagné et al. 2014). While there are many advantages in using the Bayesian method (e.g. an intuitively easier interpretation of the result due to the quantitative membership probability and the availability of marginalizing over nuisance parameters), the resultant membership probability needs to be carefully adopted because of its sensitive dependence on input models.

In this paper, we examine the impact of models and prior knowledge in the Bayesian MG membership probability, focusing on the accepted member list and the distribution functions for beta-Pictoris moving group (BPMG hereafter) and field stars. We then suggest

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Table 1. Star lists used in this study.

Name	*N*	Description	Purpose of usage
BANYAN II list	50	A list of previously known BPMG members taken from the BANYAN II webpage (www.astro.umontreal.ca/~gagne/banyanII.php; Gagné et al. 2014).	To validate our calculation by comparing it to BANYAN II's calculation (Section 2.1). To create lists of initially accepted BPMG members (*Exclusive list* and *Inclusive list*) (Section 2.2.1).
Exclusive list	39	Lists of initially accepted BPMG members based on the membership	To construct improved BPMG models (Sections 2.2.1 and 2.2.2).
Inclusive list	47	Assessment criteria (exclusive and inclusive). Subsets of the *BANYAN II list*.	
SIMBAD list	275	A list of BPMG members in SIMBAD data base as of 2017 April (http://simbad.u-strasbg.fr/simbad/), which constitutes the whole *BANYAN II list*.	To test effects of models (Section 3.1). To provide the updated list of bona fide and probable members of BPMG (Section 3.2).
Bona fide member list	51(57[a])	A confirmed BPMG member list in this study (Table 5).	To derive revised model parameters for BPMG (Section 3.2).

[a] Including six classical BPMG members showing moderate signs of youth, discussed in Section 3.2.1.

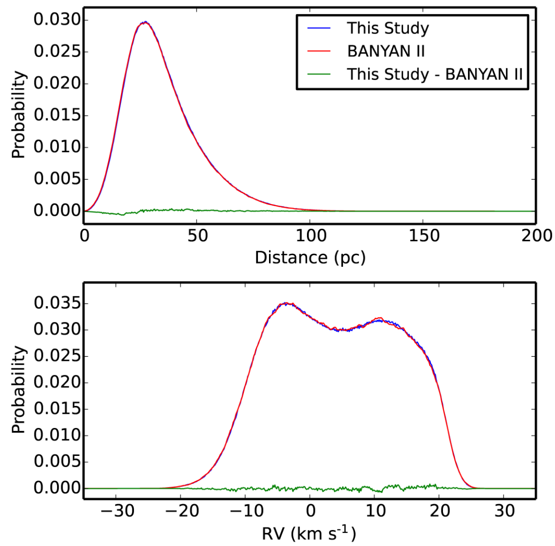

Figure 1. Prior probability distribution functions (PDFs) of RV and distance for BPMG from BANYAN II (red) and those from this study (blue) assuming identical model parameters. The differences of two prior PDFs are presented with green lines.

improvements to the membership calculations, and finally provide a list of confirmed and probable members of the BPMG.

2 BAYESIAN MG MEMBERSHIP CALCULATIONS

Our method is based on the same Bayesian principle as used in BANYAN II (Gagné et al. 2014), and one of our main purposes of this paper is to demonstrate the careful treatments of model parameters. Therefore, to minimize any possible confusion, we decide to use the BANYAN II notation in describing various terms related to the Bayesian MG membership probability calculation. Throughout this paper, in developing, validating, and comparing our method and result, we used BPMG as the main test case because this MG is one of the youngest, nearest MGs with many discovered members spread over a large area of the sky. For various purposes, different lists of stars for BPMG were used (see Table 1).

2.1 Validation of our calculation: comparison against the BANYAN II result

We developed a PYTHON script to calculate Bayesian MG membership probability. Bayesian probability (the posterior probability) is proportional to the product of the prior probability and the likelihood, which are both derived from models for MGs and field stars. To validate our code, we compare our membership calculation results (the Bayesian probability) against those of BANYAN II using identical parameters. Prior probability distribution functions (PDFs) for observables such as distance, radial velocity (RV), magnitude of proper motion, and Galactic latitude are reproduced, and two of these are compared in Fig. 1. Prior PDFs from BANYAN II and those from this study are similar but not exactly the same because these prior PDFs are generated from random simulated stellar distributions. We also used the BANYAN II group size ratios between MGs and the field stars.

The membership probability calculations from BANYAN II and those from our code are compared in Fig. 2 using a list of BPMG

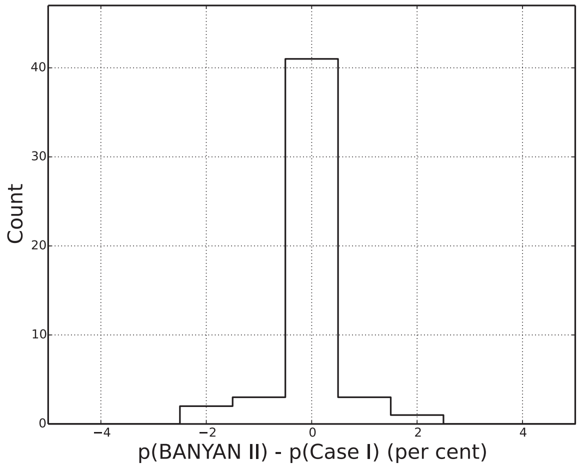

Figure 2. A comparison of membership probabilities from BANYAN II and those from this study (*Case I*) utilizing BPMG members from the *BANYAN II list* (Table 1). Both calculations are based on the same models (Table 2).

members taken from the BANYAN II webpage (*BANYAN II list*, see Table 1). This figure shows that our code replicates almost the same result of BANYAN II except for a handful of abnormal cases where the difference between the two calculations is likely caused by the small difference in prior PDFs shown in Fig. 1.

2.2 Improvement over BANYAN II: updating models

Different models modify likelihoods and prior PDFs, making changes in membership probabilities. In this study, we consider three important factors in building models: (1) a list of adopted initial MG members, (2) a distribution function of BPMG members in *XYZ*, and (3) new distribution functions of field stars in *XYZ* and *UVW*.[1] To investigate the effects of these three factors, we carried out various combinations of them and compared the result against that of BANYAN II (see Table 2).

2.2.1 Re-examination of MG membership

To define the characteristics of an MG, one has to start with a certain list of MG members. For example, to measure the extent of the distribution of MG members in *XYZ* and *UVW*, one has to model the distribution of accepted members in such 3D spaces, which means that a different set of stars will produce different distribution model parameters for the MG. This seemingly straightforward task of establishing a list of accepted MG members is more complicated because the assignment of membership status is an iterative process. Starting with a stringent initial list of accepted members, an MG will have tighter distributions in *XYZ* and *UVW* which in turn forces any candidate members need to fit the tighter parameters. On the other hand, if the membership assessment starts with a more lenient list of members, the distribution model of the MG will become more inclusive, accepting more marginal members as true members.

In this section, we reassess membership of previously known BPMG members from the *BANYAN II list*. A true member should possess not only similar kinematic characteristics (*XYZ* and *UVW*) but also a similar age with other members.

[1] *U*, *V*, and *W* are positive towards the directions of the Galactic Centre, Galactic rotation, and the North Galactic Pole, respectively.

Table 2. Combinations of different factors in building models.

Model factors	Type	BANYAN II	Cases in this study						
			Case I	*Case II (Excl.)*	*Case II (Incl.)*	*Case III (Excl.)*	*Case III (Incl.)*	*Case IV*	*Case V*
Selection of BPMG members	BANYAN II	O	O					O	
	Exclusive			O		O			O
	Inclusive				O		O		
XYZ distribution function of BPMG members	Gaussian	O	O	O	O			O	
	Uniform					O	O		O
Distribution models of field stars	BANYAN II	O	O	O	O	O	O		
	A new model							O	O

Table 3. Model parameters for BPMG. Parameters for other MGs (i.e. TWA, Tuc–Hor, AB Doradus, Columba, Carina, and Argus) are taken from BANYAN II (Gagné et al. 2014).

Name	X (pc)	Y (pc)	Z (pc)	σ_X (pc)	σ_Y (pc)	σ_Z (pc)	ϕ_{XYZ} (°)	θ_{XYZ} (°)	ψ_{XYZ} (°)	U (km s^{-1})	V (km s^{-1})	W (km s^{-1})	σ_U (km s^{-1})	σ_V (km s^{-1})	σ_W (km s^{-1})	ϕ_{UVW} (°)	θ_{UVW} (°)	ψ_{UVW} (°)
Model parameters from BANYAN II																		
$BPMG_{BANYANII}$	7.6	−3.5	−14.5	8.2	13.5	30.7	−90.2	65.1	−77.9	−11.0	−15.6	−9.2	1.4	1.7	2.5	−113.0	−70.3	76.6
Model parameters (Section 2)																		
$BPMG_{Excl}$[a]	9.4	−5.6	−13.5	7.8	13.5	29.1	88.7	−62.1	78.6	−10.7	−16.0	−9.3	1.4	1.5	2.4	−105.9	−51.2	84.5
$BPMG_{Incl}$[b]	7.7	−5.2	−12.8	8.3	13.6	29.3	86.9	−60.5	80.0	−10.7	−16.0	−9.2	1.3	1.6	2.4	−107.9	−49.3	81.0
$BPMG_{Unif,Excl}$[a]	19.7	−2.8	−14.4	22.0	32.5	67.0	−24.9	77.2	−18.4	Same to $BPMG_{Excl}$								
$BPMG_{Unif,Incl}$[b]	13.1	−3.9	−10.0	29.1	33.2	68.5	−93.6	62.1	86.8	Same to $BPMG_{Incl}$								
Revised model parameters using the confirmed member list of BPMG in Table 5 (Section 3)																		
$BPMG_{revised}$	13.4	−3.4	−18.1	19.1	32.0	71.2	−71.6	74.8	111.2	−10.4	−15.9	−9.1	1.2	1.4	2.2	−93.1	−45.5	−81.5

[a]The properties are obtained from the *Exclusive list*.
[b]The properties are obtained from the *Inclusive list*.
Notes.
1. X, Y, Z and U, V, W are central positions of the ellipsoidal models.
2. σ_X, σ_Y, σ_Z and σ_U, σ_V, σ_W are the lengths of semimajor axes in the direction of the principal axes. Values from uniform distribution models (*XYZ* models for $BPMG_{Unif,Excl}$, $BPMG_{Unif,Incl}$, and $BPMG_{revised}$) are the lengths of semiprincipal axes of the minimum volume enclosing ellipsoid (MVEE), while other values are 1σ lengths from the Gaussian models. The σ values from MVEE and Gaussian model are not comparable because all members should be enclosed within the σ in MVEE, while a large portion of members (~80 per cent) are located outside of 1σ in the Gaussian model. In the 3D Gaussian distribution, 20, 74, and 97 per cent of data are within 1σ, 2σ, and 3σ boundaries, respectively.
3. ϕ, θ, ψ are Euler rotational angles of the ellipsoids in degrees.

First, we tried to flag outliers in *XYZ* and *UVW* by calculating standard deviations (σ) in each X, Y, Z, U, V, and W. To calculate standard deviations that properly represent the MG as a whole, we excluded obvious outliers that are above the upper limit[2] or below the lower limit.[3] HIP 11360 and η Tel A deviate $\gtrsim 5\sigma$ in *UVW* from the mean. Including η Tel B, these three stars were determined to be kinematic outliers. Additionally, HIP 50156 was determined as a marginal outlier because this star has a Z-value about 4.5σ away from the mean.

Age outliers were determined based on age indicators. Genuine BPMG members should show clear signs of youth appropriate to the age of BPMG [12–25 Myr: Ortega et al. (2002); Zuckerman & Song (2004); Mamajek & Bell (2014); Bink & Jeffries (2016)]. Young (<100 Myr), Sun-like, or lower mass (mid-F to M type) stars can be distinguished from older counterparts because they have brighter photometric magnitude, NUV excess, X-ray excess, and/or strong Li absorption (Zuckerman & Song 2004; Soderblom 2010; Rodriguez et al. 2011; Bink & Jeffries 2016). 42 out of 50 stars in the *BANYAN II list* were estimated to be $\lesssim$25 Myr. Among the remaining eight stars, no age-related data exist for η Tel B, and the age estimation for the other seven stars involves significant uncertainties (HIP 10679, HIP 10680, 2M J06085283−2753583, HIP 21547, HIP 88726A, HIP 88726B, and HIP 92024). Both HIP 10679 and HIP 10680 show strong Li absorption features but can be ~100 Myr old based on a $V - K$ versus M_K colour–magnitude diagram (CMD). The location of 2M J06085283−2753583 on the CMD is ambiguous, making it difficult to unambiguously assess if this star is $\lesssim$ 25 Myr. Because HIP 21547, HIP 88726 A, HIP 88726 B, and HIP 92024 have early spectral types (F0 to A5), reliable age estimates are difficult. Even though the age estimates of these seven stars are ambiguous, none of them are marked as evident old star interlopers.

Based on age and kinematic data, one can try to build two different extreme cases for the initial accepted BPMG member list: (1) an *Inclusive list* containing all marginal members with large age uncertainties and outlying kinematics and (2) an *Exclusive list* containing only unambiguous members in age and kinematics. Using these two lists, parameters for two BPMG distribution models ($BPMG_{Excl}$ and $BPMG_{Incl}$ in Table 3) are estimated by fitting a single Gaussian model utilizing the Gaussian mixture model algorithm from PYTHON SCIKIT-LEARN package (Pedregosa et al. 2011). The distance prior PDFs for both models and 2D projections of $BPMG_{Excl}$ are presented in Figs 3, 4, and 5.

2.2.2 XYZ *distribution models of BPMG members*

In this section, we discuss a proper probability distribution of MG members as a function of distance from the centre of the MG. Should a star closer to the MG centre be assigned with a higher membership probability, or should any star within a given distance limit be treated with the same probability? A proper way to handle the model probability distribution near the boundary of an MG should be closely related to our understanding of the origin of MGs. If an MG was formed in a loosely bound environment at birth without any noticeable overdensity of their members against field stars, a uniform probability distribution model, i.e. assigning the same membership probability for all candidate members within the MG boundary, makes more sense. However, if an MG was formed in

[2] Third quartile [75 percentile] + 1.5 × interquartile range (IQR).
[3] First quartile [25 percentile] − 1.5 × IQR.

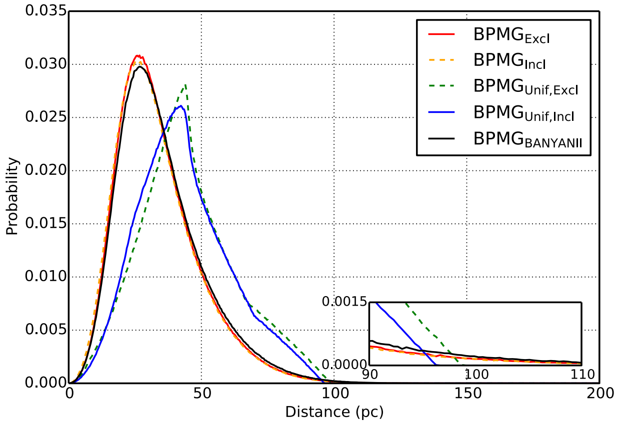

Figure 3. Prior PDFs of distance for BPMG models. Inset is an enlarged view of probabilities at around 100 pc. Models using minimum volume enclosing ellipsoid (uniform distribution in *XYZ*; BPMG$_{\rm Unif,Excl}$ and BPMG$_{\rm Unif,Incl}$−*Case III*) reach zero probability at around 100 pc, while other models, assuming a Gaussian distribution, do not.

a more gravitationally bound environment with a central concentration of members, a Gaussian probability distribution model may be more appropriate. Between uniform and Gaussian distribution models in *XYZ*, to investigate which model is more appropriate to represent the actual distribution of MG members, one has to check the existence of an overdense region in the spatial distribution of the models. It is difficult to scrutinize any overdensity in an already dispersed low-density group of stars. Therefore, checking such an overdensity in the back-traced positions in time is easier than a case of using the current positions. However, the propagation of errors backwards in time makes such analyses very difficult. For given current knowledge and data of young MGs in the solar neighbourhood, it is very difficult to distinguish between these two models.

Therefore, the virtue of using a uniform or a Gaussian *XYZ* distribution model needs to be evaluated by the current distribution of members. Fig. 6 shows the normalized number density of BPMG members (stars in the *Exclusive list*) in each *X*, *Y*, and *Z*. For eliminating the binning effect in the investigation of the distributions, a kernel density estimation (KDE) was applied to these data. It is well known that KDE underestimates the density near the boundary. After correcting the boundary effect by truncating the kernel at the outermost boundaries (minimum and maximum values for each *X*, *Y*, and *Z*), *X* and *Y* values do not appear to be centrally concentrated. However, *Z*-values appear to be more centrally concentrated. It is interesting to note that BPMG members are concentrated in the *Z*-direction. Because of the vertical structure of Milky Way with the scale height of about 300 pc, a certain degree of concentration of stars is expected but not at this level. The peak of the *Z*-concentration

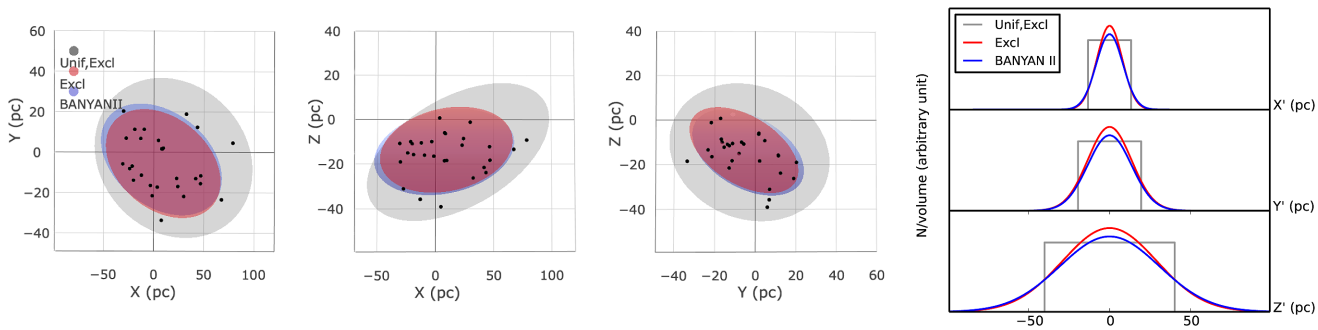

Figure 4. 2D projections of BPMG models in *XYZ*. BPMG$_{\rm BANYANII}$, BPMG$_{\rm Excl}$, and BPMG$_{\rm Unif,Excl}$ models are presented with blue, red, and grey, respectively. Stars in the *Exclusive list* are presented as dots. We plotted 1.2 times the MVEE semimajor axes for BPMG$_{\rm Unif,Excl}$ and 2σ boundaries for the other two Gaussian models. The former should have 100 per cent of integrated probability within the plotted boundaries while the latter should have 87 per cent of integrated probabilities within the plotted boundaries. The right-hand panel presents the number density (i.e. probability density function) along principal major axes (X', Y', and Z') for each model.

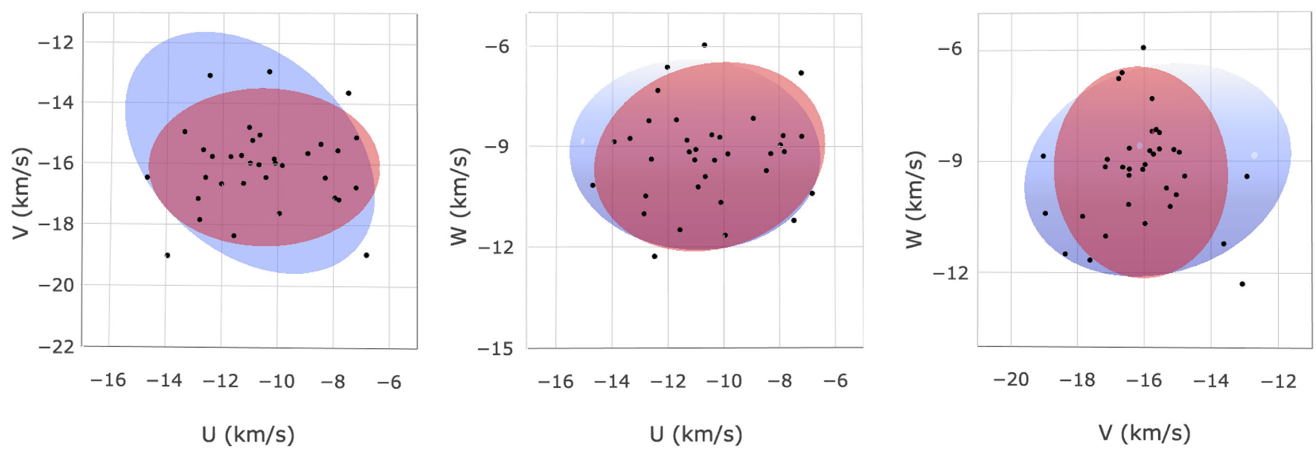

Figure 5. 2D projections of BPMG models in *UVW*. BPMG$_{\rm BANYANII}$ and BPMG$_{\rm Excl}$ models are presented with blue and red, respectively. Stars in the *Exclusive list* are presented as dots. The model boundaries are 2σ values in each semimajor axis.

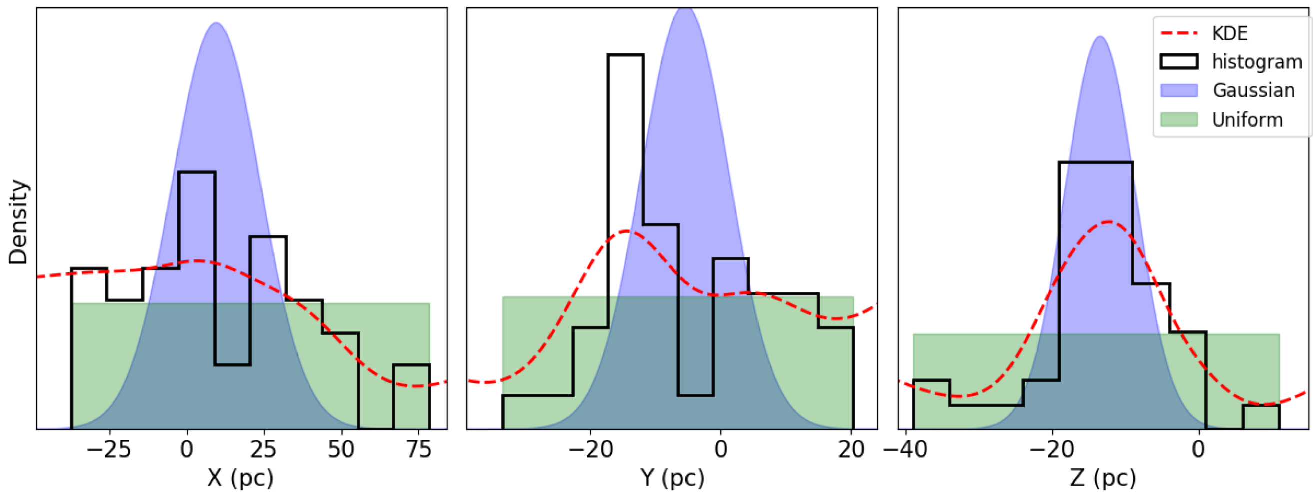

Figure 6. Normalized density of stars in the *Exclusive list* in each *X*, *Y*, and *Z*. The density function using a kernel density estimation (KDE), which shows binning-free distribution, is presented with a red dashed line overlaid on the data histogram. In the boundary region, KDE underestimates the density because there are no data (boundary effects) and these boundary effects are corrected by truncating the kernel at the outermost boundaries (minimum and maximum values for each *X*, *Y*, and *Z*). Gaussian and uniform distributions of pseudo data are presented as shaded area with blue and green colours, respectively.

is around −15 pc which may be the manifestation of the Sun being located 10–30 pc above the Galactic plane (Humphreys & Larsen 1995; Joshi 2007).

As shown in Fig. 6, the difference in *XYZ* distribution models is not that significant and the best model seems to be a combined one (uniform in *X* and *Y* and Gaussian in *Z*). If a future survey for BPMG members especially close to the known BPMG boundary is carried out, such a combined *XYZ* distribution model is recommended. In this paper, we select a version of the uniform distribution model in all three (*XYZ*) directions for simplicity.

We compared results from two different distribution models: Gaussian and uniform models (in Table 2, *Case II* and *Case III*, respectively). Throughout the paper, the distribution function of BPMG members in *UVW* is assumed to be a Gaussian similar to the treatment in BANYAN II.

Case III (Excl.) and *Case III (Incl.)* adopt members in the *exclusive* and *inclusive lists*, to construct uniform *XYZ* models for BPMG utilizing a minimum volume enclosing ellipsoid (MVEE) algorithm (Kumar & Yildirim 2005). The model parameters for these two cases are presented in Table 3 ($\mathrm{BPMG_{Unif,Excl}}$ and $\mathrm{BPMG_{Unif,Incl}}$), and the distribution of one model ($\mathrm{BPMG_{Unif,Excl}}$) is shown in Fig. 4. The uniform membership probability functions fitted as MVEEs would be step functions; a constant within each ellipsoid, but zero outside of the ellipsoid. To consider candidate members sitting barely outside of the distance limit of known members, we increase the lengths of principal axes of the MVEEs by 1.2 times. Fig. 3 shows that probabilities from these two uniform models drop to zero above a certain distance, while those from Gaussian models never reach zero.

2.2.3 *Distribution models of field stars*

Similar to the MG properties, field star properties can be acquired by finding the best-fitting distribution model to the actual distribution of field stars in *XYZ* and *UVW*. In *XYZ*, we assumed that stars are uniformly distributed although this uniform spherical distribution may not be perfect in the *Z*-direction at large distance because the scale height of the Galactic disc is about 300 pc. This uniform field star model in *XYZ* explains the actual distribution

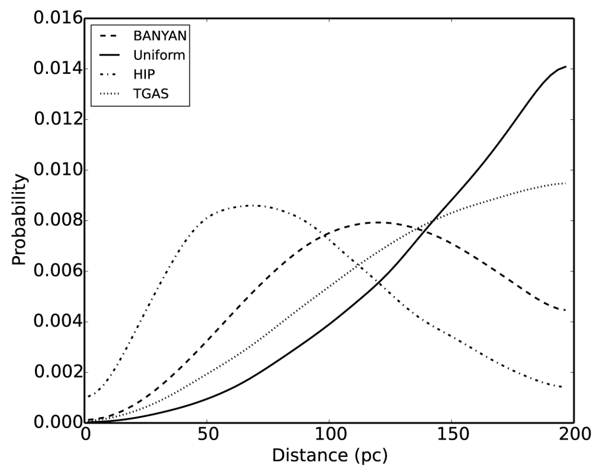

Figure 7. Prior PDFs of distance for field star models used in BANYAN II (dashed line) and in this study (solid line). BANYAN II includes two field star models (young and old), but their distance PDFs are similar and we present the old one. Data from *Hipparcos* (dot–dashed line) and TGAS (dotted line) catalogues are presented for comparisons. We note that *Hipparcos* data especially suffer from the limited survey depth, causing an apparent peak around ∼60 pc.

of nearby stars better than the case of BANYAN II. Utilizing the Besançon Galaxy model (Robin et al. 2003, 2012), Gagné et al. (2014) created a field star model by fitting the *XYZ* distribution of all field stars inside of 200 pc with a single Gaussian model for the young (<1 Gyr) and old (≥1 Gyr) field stars. The field star model used in BANYAN II predicts a high concentration of field stars at ∼120 pc, while the largest stellar catalogue with measured parallactic distances at present [*Tycho-Gaia* Astrometric Solution (TGAS); Michalik, Lindegren & Hobbs 2015] shows no such concentration (Fig. 7), which supports the uniform field star distribution in *XYZ*.

The field star distribution in *UVW* was examined using *Hipparcos* and TGAS catalogues. To examine the distribution of stars in *UVW*, one has to know six parameters: RA, Dec., distance, proper motions in RA and Dec., and RV. Approximately 50 000 stars in the

Hipparcos catalogue have all six parameters, and they clearly show 3–4 subgroups in *UVW* (Fig. 8). By applying a wavelet analysis technique on the 2D *UVW* plots, Skuljan, Hearnshaw & Cottrell (1999) and Chereul, Crèzè & Bienaymè (1997) identified ∼4 kinematic clusters of nearby field stars in the *Hipparcos* catalogue. Because the *Hipparcos* catalogue is limited to stars mostly within <100 pc from the Sun, one has to use a larger kinematic catalogue to check if the apparent four kinematic clusters of nearby stars exist beyond 100 pc. The TGAS catalogue provides five parameters for ∼2 million stars, and the only missing parameter to calculate *UVW* is RV. Since almost all nearby stars do not travel faster than ∼100 km s^{-1} with respect to the Sun, we can assume that most TGAS stars have RVs in the range of −100 and +100 km s^{-1}. Calculating possible *UVW*s over the range of these RVs, we can examine the kinematic clustering of field stars using a much larger sample of stars (∼2 million) than the *Hipparcos* data (∼50 000). Even though the stellar distribution becomes diluted because of the ±100 km s^{-1} RV range instead of a single value of RV for a star, the kinematic clustering of TGAS stars looks similar to that of *Hipparcos* stars (first and second columns in Fig. 8).

Adopting these two possible improvements described above, we created a new field star model. The new field star model in *UVW* is obtained from the best-fitting Gaussian ellipsoidal models of *Hipparcos* stars (Table 4 and 2D projections in Fig. 9), and the model in *XYZ* is a uniform distribution within a sphere of 200 pc in radius. As can be seen in Fig. 7, the distance distribution of the field star model in BANYAN II peaks at ∼120 pc, while the PDF of the new field star model expects more stars at larger distance. A field star distribution model is involved in the overall normalization of the calculation; therefore, this uniform field star distribution model would increase the MG membership probability for nearby MG members; however, it would decrease the membership probability of more distant MG candidate members. Fig. 8 (third and fourth columns) compares the field star *UVW* model used in BANYAN II to the new model, showing that the latter fits the *Hipparcos* more closely.

3 RESULTS

Using the updated models mentioned in the previous section, we now calculate membership probabilities of all BPMG candidate members available from SIMBAD (Zuckerman et al. 2001b; Song et al. 2003; Zuckerman & Song 2004; Moór et al. 2006, 2013; Torres et al. 2006, 2008; Lépine & Simon 2009; Teixeira et al. 2009; Schlieder et al. 2010; Schlieder, Lépine & Simon 2012a,b; Shkolnik et al. 2012; Malo et al. 2013, 2014; Best et al. 2015; Gagné et al. 2015a,b). The result shows a sensitive dependence on models. Based on the calculated membership probabilities, we updated the list of BPMG members adding 12 new bona fide members. With this updated membership list, we revised the BPMG model as described below.

3.1 Effects of improved models

We examine the effects of membership by comparing cases that adopt the *exclusive* and *inclusive lists* (Table 2). Since BANYAN

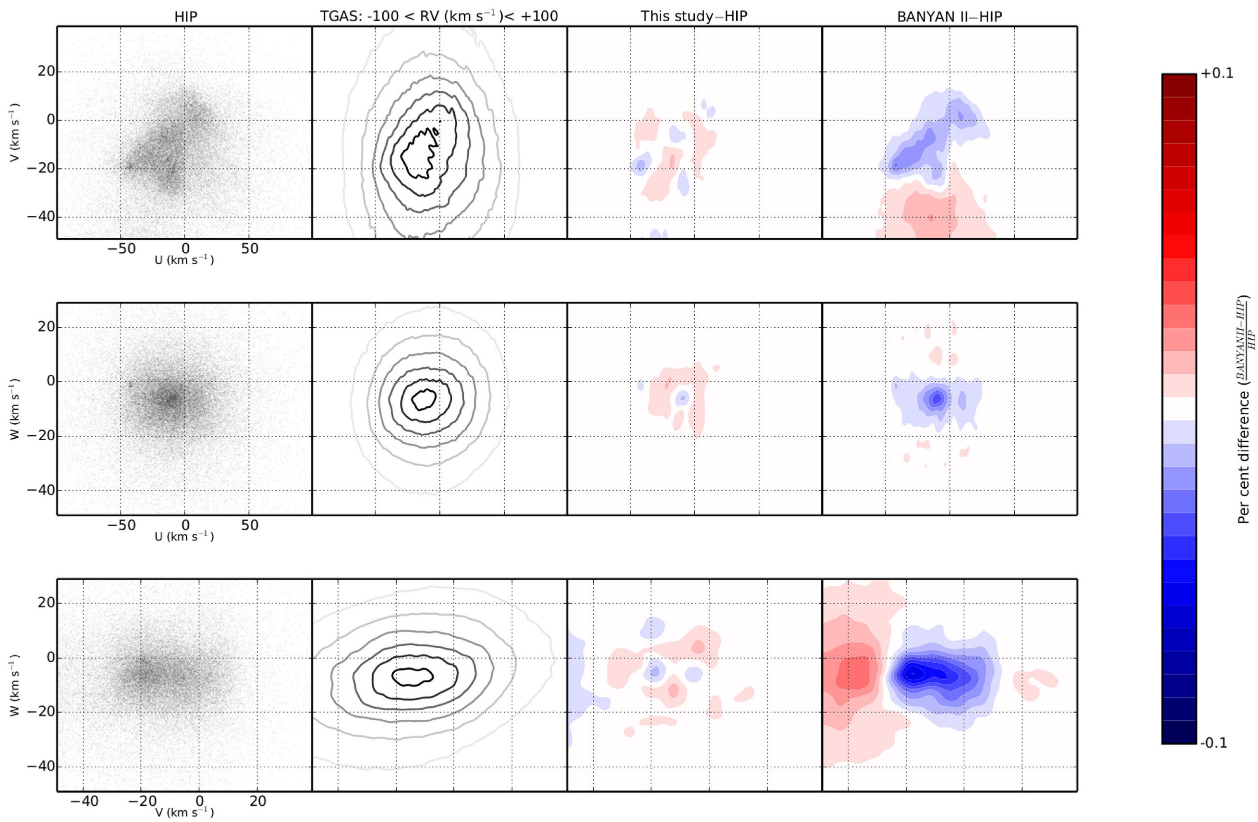

Figure 8. Stellar distribution in *UVW*. First column represents the distribution of *Hipparcos* stars with measured RV (∼50 000 stars; Anderson & Francis 2012; references therein). Second column shows density maps of TGAS stars of possible *UVW* values over the RV range of −100 to +100 km s^{-1}. Residual contour plots at third and fourth columns represent the differences between *Hipparcos* stars and simulated stars generated by a field star model from this study (third column), and those from BANYAN II (fourth column). Colours correspond to the colour bar, which scales from the minimum to the maximum values of the differences, which appear in the BANYAN II−HIP map on the *VW* plane.

Table 4. Group properties of the field star model in *UVW* in this study.

Name	*U* (km s^{-1})	*V* (km s^{-1})	*W* (km s^{-1})	σ_U (km s^{-1})	σ_V (km s^{-1})	σ_W (km s^{-1})	ϕ (°)	θ (°)	ψ (°)	Weight[a]
FLD1	− 17.1	− 18.0	−6.3	6.8	8.1	14.2	48.5	− 86.2	− 56.2	0.29
FLD2	− 32.0	− 16.2	−8.1	15.8	16.5	19.4	− 54.7	− 80.7	112.6	0.26
FLD3	2.4	− 0.8	−6.7	8.8	9.8	13.9	88.8	1.2	− 97.4	0.24
FLD4	22.1	− 16.8	−9.5	16.1	16.8	21.3	110.9	− 67.8	104.1	0.21

[a]The relative number density.

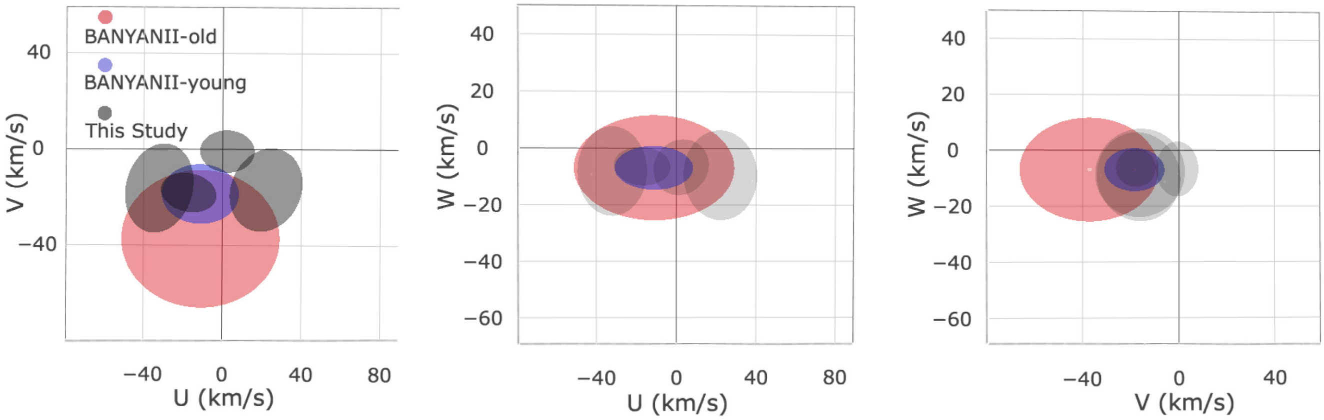

Figure 9. Field star distribution models from this study (grey) and those from BANYAN II (red and blue represent old and young field stars, respectively). Plotted are 1σ ellipses.

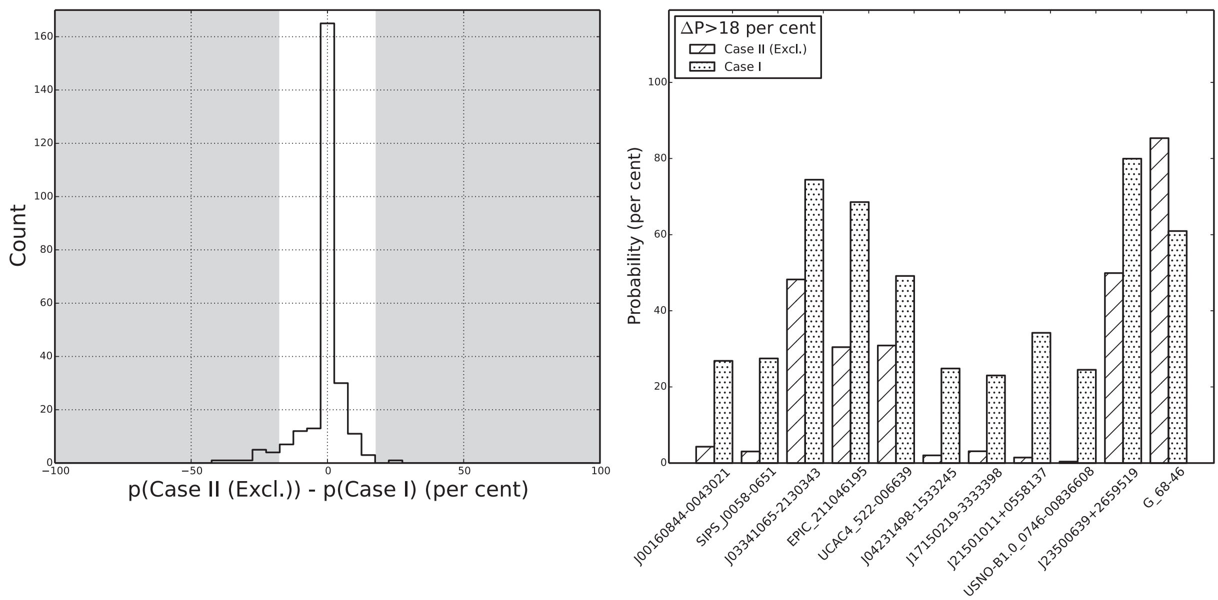

Figure 10. Effects of the BPMG member selection [BANYAN II (*Case I*) versus *Exclusive list* (*Case II*)]. The left-hand panel shows a histogram of the membership probability differences between these two cases. Stars showing large differences in the membership probabilities ($\Delta p > 18$ per cent, grey area in the left-hand panel) are presented in the right-hand panel. Test stars are from the *SIMBAD list*.

II used a Gaussian *XYZ* distribution (*Case I*), we compare *Case I*, *Case II (Excl.)*, and *Case II (Incl.)*, using a Gaussian distribution for members in *XYZ*. Since the BPMG model based on *Inclusive list* – (*Case II (Incl.)*) – allows more marginal members to start with, this flexibility would increase the membership probability of a marginal member, while the model from *Exclusive list* – (*Case II (Excl.)*) – would decrease the probability. Figs 10–12 compare membership probabilities from *Case I* and those from *Case II*. Overall, the effects of the member list appear to be small (less than 5 per cent of test stars having a probability difference of greater than 20 per cent), and it is likely due to the similarities of the model extents (see σ values for $\mathrm{BPMG_{Excl}}$, $\mathrm{BPMG_{Incl}}$, $\mathrm{BPMG_{BANYANII}}$ in Table 3). However, for a few stars, the effect of the member list is significant causing the membership probability changes up to ~40 per cent.

Figs 13 and 14 compare the membership probabilities from cases assuming a Gaussian distribution (*Case II*) or a uniform

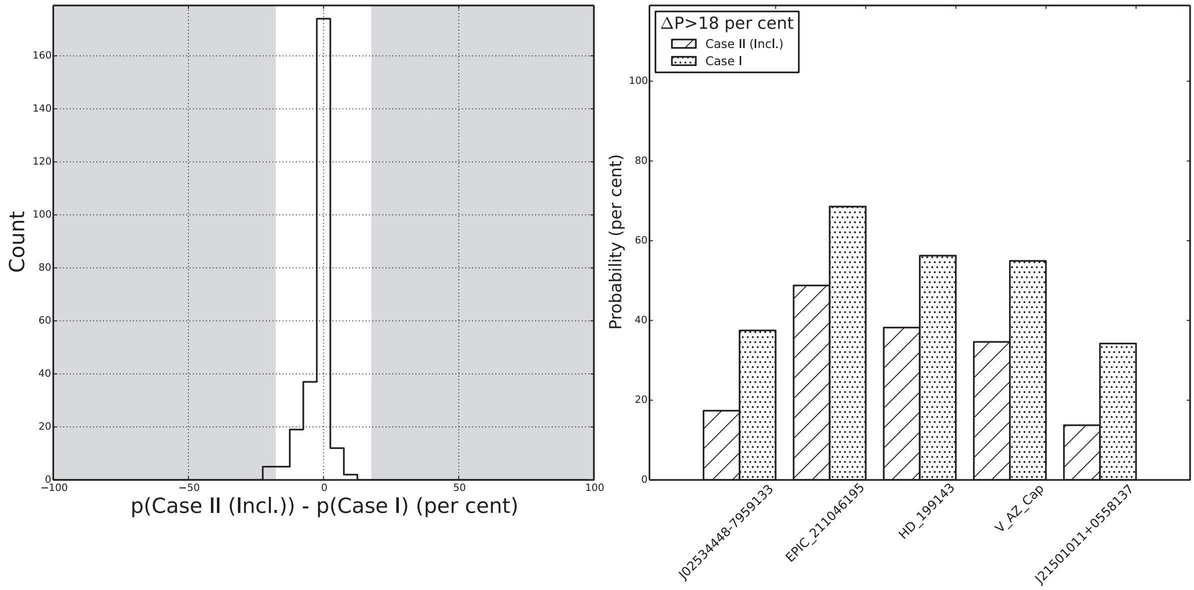

Figure 11. Effects of the BPMG member selection [BANYAN II (*Case I*) versus *Inclusive list* (*Case II*)]. The left-hand panel shows a histogram of the membership probability differences between these two cases. Stars showing large differences in the membership probabilities ($\Delta p > 18$ per cent, grey area in the left-hand panel) are presented in the right-hand panel. Test stars are from the *SIMBAD list*.

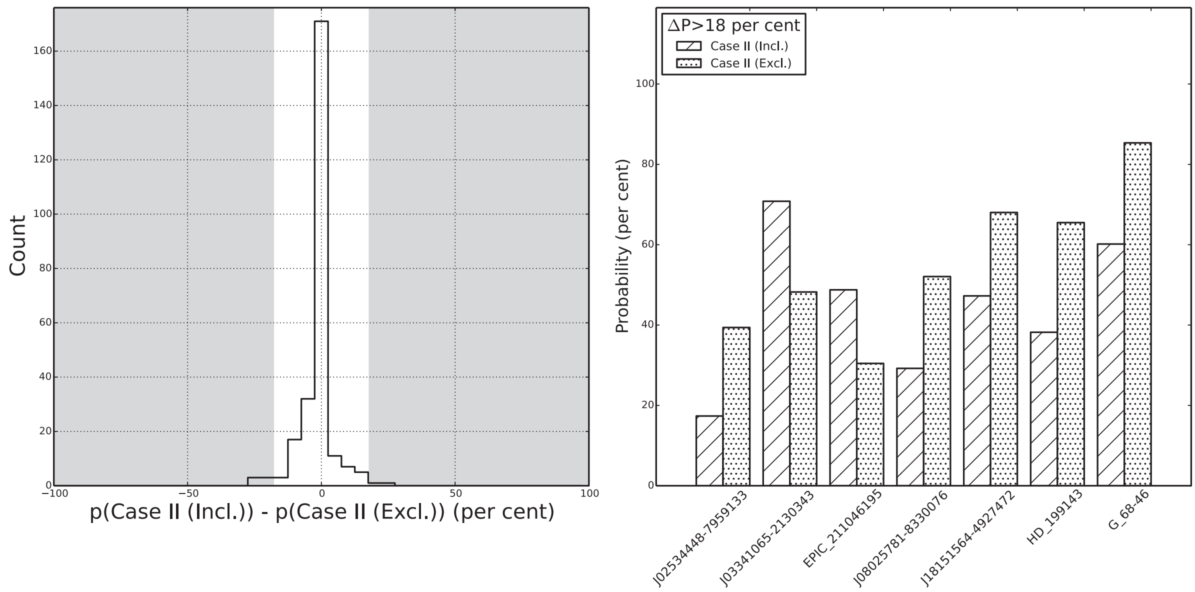

Figure 12. Effects of the BPMG member selection (*Inclusive list* versus *Inclusive list*). The left-hand panel shows a histogram of the membership probability differences between these two cases. Stars showing large differences in the membership probabilities ($\Delta p > 18$ per cent, grey area in the left-hand panel) are presented in the right-hand panel. Test stars are from the *SIMBAD list*.

distribution (*Case III*) of members in *XYZ*. As expected, the Gaussian distribution models decrease membership probabilities of candidate members located near the boundary. The membership probabilities of HD 168210 and δ Sco were increased by $\sim$60 per cent under the uniform spatial distribution model. These two stars are located far from the centre of the BPMG model ($\sim$70 and $\sim$40 pc, respectively). Stars relatively close to the centre, such as G76-8 ($\sim$20 pc) on the other hand, have larger membership probabilities under the Gaussian distribution model (>80 per cent in *Case II* versus <10 per cent in *Case III*). This difference can be important in investigating the membership status of candidate members around or beyond the assumed initial MG boundary.

Because there are many more old field stars than MG members in a given range of *XYZUVW*, a small change in the *XYZUVW* distribution model of field stars can significantly affect membership probabilities of candidate MG members. Fig. 15 shows the effect of the field star model by comparing membership probabilities from *Case IV* and those from *Case I*. Membership probabilities tend to increase under the new model of field star distribution (*Case IV*), by up to 80 per cent. *Case IV* assumes a uniform field star distribution in *XYZ*, expecting a smaller field star number density, within $\sim$140 pc, compared to BANYAN II (Fig. 7). Since almost all known BPMG candidate members are located within $\sim$100 pc, membership probabilities from *Case IV* generally increase compared to those from *Case I*.

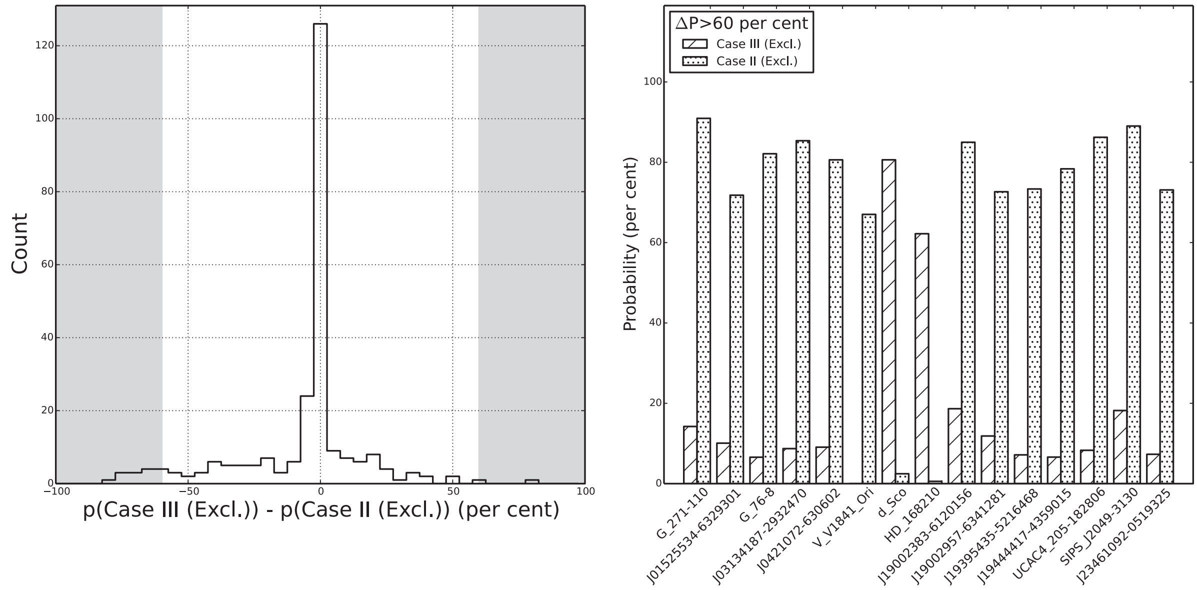

Figure 13. Effects of the distribution model of BPMG members [a Gaussian (*Case II (Excl.)*) versus a uniform (*Case III (Excl.)*) distribution in *XYZ*]. The left-hand panel shows a histogram of the membership probability differences between these two cases. Stars showing large differences in the membership probabilities ($\Delta p > 60$ per cent, grey area in the left-hand panel) are presented in the right-hand panel. Test stars are from the *SIMBAD list*.

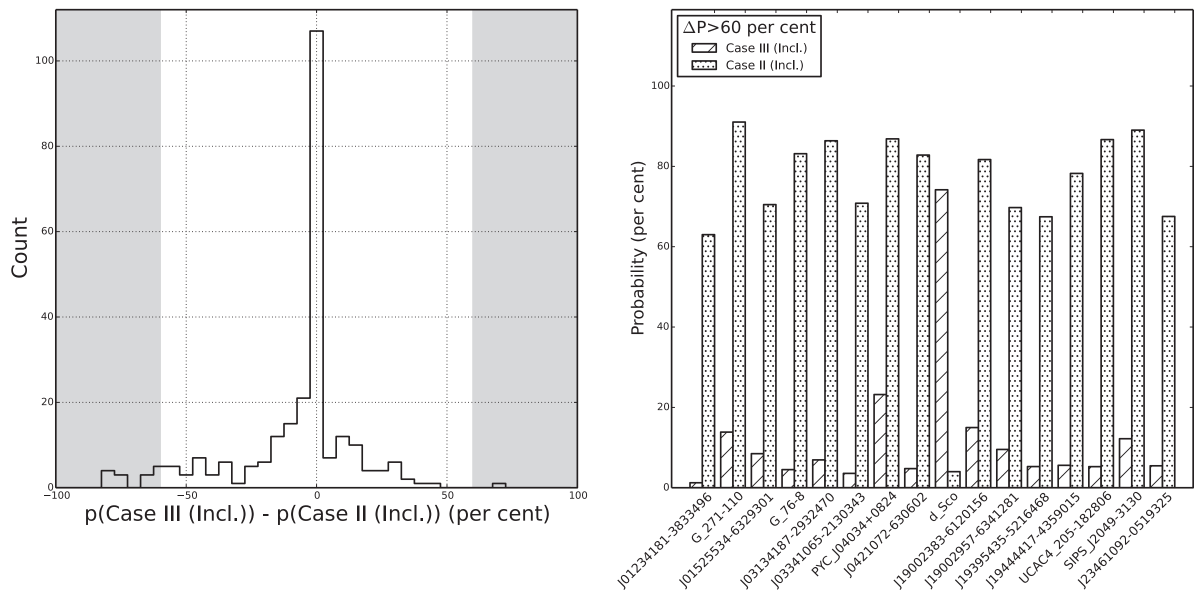

Figure 14. Effects of the distribution model of BPMG members [a Gaussian (*Case II (Incl.)*) versus a uniform (*Case III (Incl.)*) distribution in *XYZ*]. The left-hand panel shows a histogram of the membership probability differences between these two cases. Stars showing large differences in the membership probabilities ($\Delta p > 60$ per cent, grey area in the left-hand panel) are presented in the right-hand panel. Test stars are from the *SIMBAD list*.

We have shown that each case listed in Table 2 significantly affects the membership probability. Using all of these updated models simultaneously (*Case V*), we calculated membership probabilities of stars in the *SIMBAD list*. These membership probabilities are compared to those from *Case I* (Fig. 16), showing a significant difference in membership probability. About 40 stars show changed membership probabilities larger than ∼50 per cent compared to values from *Case I*. The majority of stars in *SIMBAD list* (∼60 per cent) have membership probabilities of less than 50 per cent, implying the high contamination rate of false members in the *SIMBAD list* (Fig. 17).

3.2 Membership assessment and a revised BPMG model based on the improvement

We can reconstruct a new list of bona fide members of BPMG based on our updated scheme of using several updated models simultaneously (the updated field star model, a uniform *XYZ* distribution of BPMG members, and either the *exclusive* or *inclusive* list of initial adopted members). When this new scheme was applied to 275 candidate members from the *SIMBAD list*, only about 40 per cent stars are believed to be kinematically associated with BPMG ($p > 50$ per cent). A more stringent selection of candidate members ($p > 80$ per cent) indicates only one third of the suggested

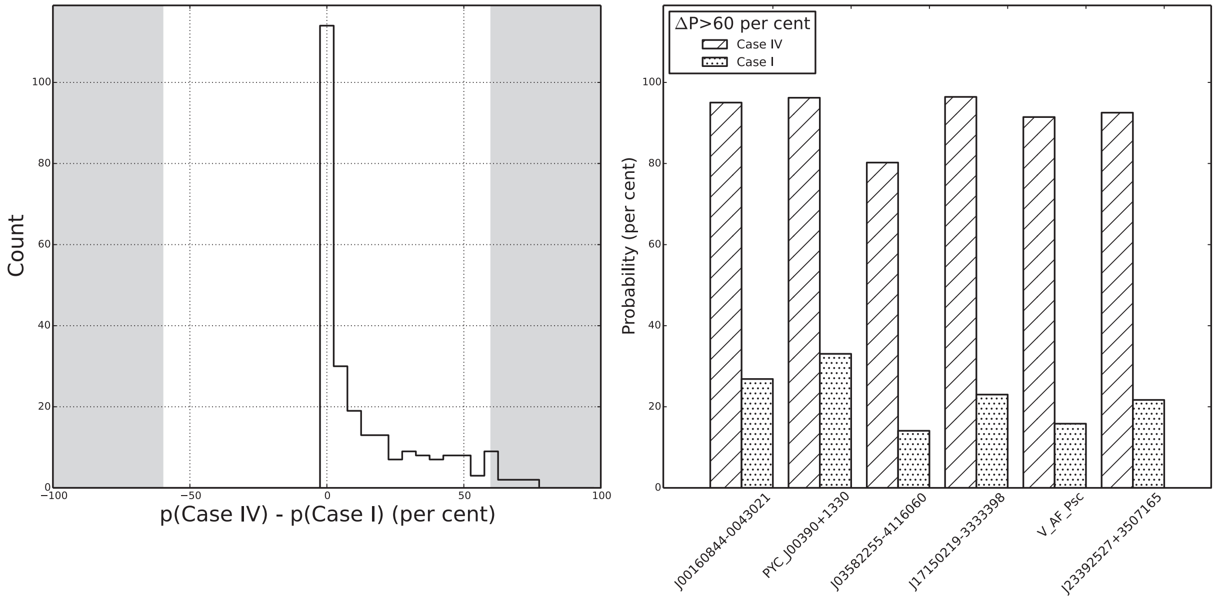

Figure 15. Effects of the field star model [BANYAN II (*Case I*) versus a new field star model (*Case IV*)]. The left-hand panel shows a histogram of the membership probability differences between these two cases. Stars showing large differences in the membership probabilities ($\Delta p > 60$ per cent, grey area in the left-hand panel) are presented in the right-hand panel. Test stars are from the *SIMBAD list*.

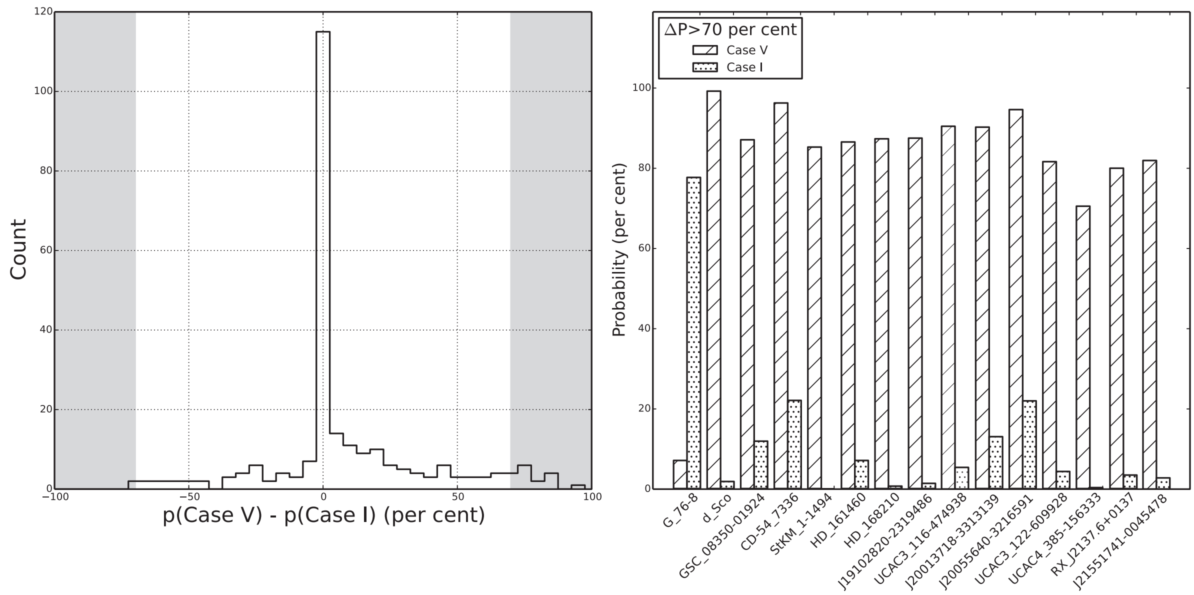

Figure 16. A comparison of membership probabilities from *Case V* (using all updated models simultaneously) and those from *Case I* (BANYAN II). The left-hand panel shows a histogram of the membership probability differences between these two cases. Stars showing large differences in the membership probabilities ($\Delta p > 70$ per cent, grey area in the left-hand panel) are presented in the right-hand panel. Test stars are from the *SIMBAD list*.

members can be retained. Moreover, a kinematic similarity is not a sufficient condition for being a true member because of the large contamination of field stars with similar kinematics. To be deemed as a bona fide member, any survived kinematic candidates should also show clear signs of youth ($\lesssim$25 Myr). In this section, we discuss details on how we reject or include a particular star in a list of updated bona fide members.

3.2.1 Method of rejection

Stars with small kinematic membership probability (<80 per cent) or lacking clear signs of youth (age $\lesssim$25 Myr) were rejected. We present five cases of rejected stars from the *BANYAN II list*.

3.2.1.1 HIP 11360. This was initially suggested as a BPMG member by Moór et al. (2006), while Malo et al. (2013) suggested it as a Columba member. Although the star shows strong Li absorption, it should not be considered as a BPMG member due to the low membership probability (0 per cent) in agreement with Malo et al. (2013). Instead, we suggest that HIP 11360 is a Tuc–Hor member because of the large membership probability (p(Tuc–Hor)$\sim$100 per cent).

3.2.1.2 HIP 50156. This was initially proposed as a member of BPMG by Schlieder et al. (2012a), while Malo et al. (2013) suggested that it is likely to be a member of Columba. In spite of showing unambiguous youth ($\lesssim$25 Myr; based on X-ray luminosity,

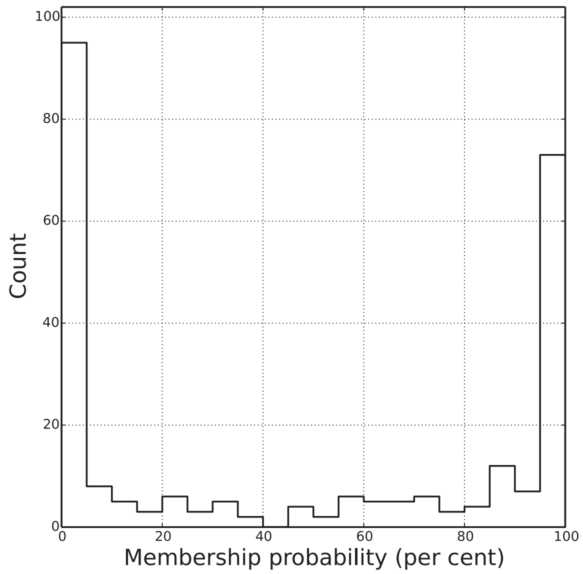

Figure 17. Membership probabilities for stars from the *SIMBAD list* using all updated models (*Case V*).

photometric magnitude, and NUV-excess), this star should not be considered as a BPMG member due to the low membership probability (0 per cent).

3.2.1.3 2M J06085283−2753583. This was initially suggested as a BPMG member by Rice, Faherty & Cruz (2010). However, this star has a low kinematic membership probability (1 per cent). In addition, unambiguous young age cannot be demonstrated based on a CMD position (e.g. $V - K$ versus M_K) because of the large model uncertainty of pre-main-seqeuence evolution models at this young age and a low-mass range. Furthermore, an empirical comparison against other known young stars is implausible because of lacking comparison stars with demonstrated youth.

3.2.1.4 ηTel A&B. These were originally proposed as members of Tuc–Hor by Zuckerman & Webb (2000), but their memberships were later revised to BPMG by Zuckerman et al. (2001b). η Tel A shows unambiguous youth on the CMD, but it should not be considered a BPMG member due to the low kinematic membership probability (4 per cent). Its companion, η Tel B, has a large membership probability (∼90 per cent), which is obtained by marginalizing over RV. In order for η Tel B to be a BPMG member, its predicted RV must be ∼1 km s^{-1}, which is significantly different from the consistently measured value of 12–14 km s^{-1} for η Tel A (Campbell 1928; Wilson 1953; Evans et al. 1964; Evans 1967; Goncharov 2006). Thus, these stars should not be considered as BPMG members.

3.2.2 *Method of inclusion*

In order to be considered as bona fide members, stars should show large kinematic membership probability (>80 per cent) and clear signs of age younger than or similar to 25 Myr. 39 stars in the *BANYAN II list* are confirmed as bona fide BPMG members. They are listed in the first part of Table 5. Among these stars, HIP 86598 and HIP 89829 are located far from Earth compared to other members (∼70–80 pc; other members are located within 50 pc). HIP 86598 was suggested as an Upper Scorpius member by Song, Zuckerman & Bessell (2012), while Malo et al. (2013) suggested this star as a BPMG member. The other star, HIP 89829, was identified as a BPMG member by Torres et al. (2008) and Malo et al. (2013). Both HIP 86598 and HIP 89829 can be BPMG members because their Z-position (about −10 pc) is in the range for BPMG members (−40 to +10 pc) rather than for stars of Upper Scorpius (+20 to +100 pc). Their positions in XYZ and/or UVW appear to be close to the edge of the BPMG model (X, Y, U, and V for HIP 86598, X and Z for HIP 89829). Therefore, these stars can be treated marginal BPMG members.

In addition to these confirmed members in the *BANYAN II list*, we added 12 new members from the *SIMBAD list* spanning spectral types K1 to M4.5. These members have kinematic membership probabilities larger than 95 per cent and clear signs of youth. They are shown in Table 5 designated as newly confirmed members. These 12 stars were suggested as BPMG candidate members in previous researches (Torres et al. 2006; Lépine & Simon 2009; Messina et al. 2010; Kiss et al. 2011; Malo et al. 2013, 2014; Riedel et al. 2014). 2MASS J21212873−6655063 was initially suggested as a member of Tuc–Hor by Zuckerman, Song & Webb (2001b); however, subsequent works (Malo et al. 2013, 2014) and the kinematic membership probability (100 per cent) based on the updated models in this study support that this star should be a bona fide member of BPMG. In addition, CD-54 7336 and CD-31 16041 were initially proposed as members of Upper Scorpius by Song et al. (2012) based on the direction in the sky and large assumed distances. Now, we also conclude that these two stars are members of BPMG instead of Upper Scorpius based on their updated membership probabilities (97–100 per cent), Z-positions (−12 to −13 pc), and trigonometric distances (∼50–70 pc).

3.2.3 *Ambiguous cases*

Among well-known members of BPMG (the *BANYAN II list*), six stars (HIP 10679, HIP 10680, HIP 21547, HIP 88726A & B, and HIP 92024) are ambiguous in their membership determination because they show moderate signs of youth ($\lesssim$100 Myr but not $\lesssim$25 Myr). We retained them in our bona fide member list for the lacking clear evidence of their non-memberships.

3.2.4 *Suggestion of probable members*

Finally, there are 17 highly probable BPMG candidate members. We separately listed these stars in three groups in Table 5 according to age and data constraints. Group 1 consists of stars showing unambiguous youth with large membership probabilities (>85 per cent), but lacking partial kinematic parameters such as distance or RV. The four stars in this group were suggested as candidate members of BPMG in several studies (Zuckerman & Song 2004; Torres et al. 2006; Messina et al. 2010; Malo et al. 2013, 2014). HD 161460 was suggested as a member of Upper Scorpius by Song et al. (2012). Group 2 contains stars having large membership probabilities (>80 per cent), but showing only moderate signs of youth and missing distance or RV. Stars in this group were suggested as members of BPMG in multiple studies (Lépine & Simon 2009; Schlieder et al. 2010; Kiss et al. 2011; Malo et al. 2013, 2014; Gagné et al. 2015a,b). However, PYC J00390+1330 and UPM J1354−7121 were also suggested as AB Dorarus members by Schlieder et al. (2012a) and Malo et al. (2013), respectively.

Table 5. The updated list of BPMG members.

Name	SpT.	R.A. (hh:mm:ss)	Dec. (dd:mm:ss)	μ_α (mas yr^{-1})	μ_δ (mas yr^{-1})	μ Ref.	π (mas)	π Ref.	RV (km s^{-1})	RV Ref.	$B-V$ (mag)	$V-K$ (mag)	K^a (mag)	NUV^b (mag)	$\log L_X/L_{bol}{}^c$	Li^d (mÅ)	Li Ref.	p(BPMG)^e (per cent)
Confirmed Members from a previously known BPMG member list (the *BANYAN II list*)																		
HIP 560	F2IV	00:06:50	−23:06:27	97.1 ± 0.03	− 47.3 ± 0.02	5	25.2 ± 0.4	5	6.5 ± 3.5	7	0.38	0.93	5.24	–	− 5.34	87	25	100
2MASS J01112542+1526214	M5	01:11:25	+15:26:21	192.0 ± 8.0	− 130.0 ± 8.0	30	45.8 ± 1.8	17	4.0 ± 0.1	17	1.76	6.22	8.21	19.88	− 3.00	–	–	100
2MASS J01351393−0712517	M4	01:35:13	−07:12:51	93.0 ± 1.7	− 48.0 ± 2.2	30	25.9	20	6.3 ± 0.5	12	1.50	5.35	8.08	19.05	− 2.56	–	–	99
HIP 10679	G2V	02:17:24	+28:44:31	85.1 ± 0.4	− 70.8 ± 0.3	5	25.5 ± 0.2	5	5.7 ± 0.3	33	0.62	1.50	6.26	12.94	− 3.91	163	13,14,4,25,22	100
HIP 10680	F5V	02:17:25	+28:44:43	87.1 ± 0.2	− 74.1 ± 0.2	5	25.2 ± 0.2	5	5.4 ± 0.5	37	0.51	1.24	5.79	12.63	− 4.18	132	13,14,4,25,22	100
HIP 11152	M3V	02:23:26	+22:44:06	98.5 ± 0.2	− 112.5 ± 0.1	5	36.9 ± 0.3	5	10.4 ± 2.0	18	1.56	3.93	7.35	17.77	− 3.16	0	32	100
HIP 11437 B	M0	02:27:28	+30:58:41	81.5 ± 4.6	− 69.1 ± 3.2	30	24.3 ± 0.2	5	4.7 ± 1.3	22	1.50	4.63	7.92	18.98	− 2.37	115	14,4,25,22	100
HIP 11437 A	K8	02:27:29	+30:58:25	79.5 ± 0.2	− 72.1 ± 0.1	5	24.3 ± 0.2	5	6.5 ± 0.4	27	1.33	2.99	7.08	17.64	− 3.10	227	14,4,25,22	100
HIP 12545 AB	K6V	02:41:25	+05:59:19	79.5 ± 3.1	− 53.9 ± 1.7	27	23.8 ± 1.5	27	10.0	25	1.09	3.15	7.07	17.47	− 2.94	433	28,14,4,25,22	97
2MASS J03350208+2342356	M8.5	03:35:02	+23:42:36	54 ± 10	− 56 ± 10	20	23.1	20	15.5 ± 1.7	20	–	–	11.26	22.12	–	615	20	85
HIP 21547	F0V	04:37:36	−02:28:25	44.2 ± 0.4	− 64.4 ± 0.3	27	34.0 ± 0.3	27	12.6 ± 0.3	27	0.28	0.67	4.54	–	–	0	25	94
GJ 3305 AB	M0V	04:37:37	−02:29:28	45.9 ± 1.3	− 63.6 ± 1.2	30	34.0 ± 0.3	27	21.7± 0.3	20	1.45	4.18	6.41	–	− 2.52	99	14,25	100
HIP 23200	M0V	04:59:34	+01:47:00	39.3 ± 0.2	− 95.0 ± 0.1	5	40.7 ± 0.3	5	19.3 ± 0.2	34	1.38	3.84	6.26	–	− 3.05	270	2,25	100
HIP 23309	M0	05:00:47	−57:15:26	35.3 ± 0.1	74.1 ± 0.1	5	36.9 ± 0.3	5	19.4 ± 0.3	25	1.38	3.73	6.24	17.51	− 3.33	325	28,14,4,25,31	100
HIP 23418	M3V	05:01:58	+09:58:60	12.1 ± 9.9	− 74.4 ± 5.7	27	30.1 ± 9.6	27	14.9 ± 3.5	27	1.52	5.14	6.37	16.50	− 2.82	0	25,22	93
GJ 3331 BC	M3.5V+M4V	05:06:49	−21:35:04	33.1 ± 2.7	− 33.2 ± 2.0	30	50.7 ± 0.3	5	23.7 ± 1.7	6	1.66	5.39	6.11	16.77	− 2.97	20	2	96
GJ 3331 A	M1V	05:06:49	−21:35:09	46.6 ± 0.6	− 16.3 ± 1.0	5	50.7 ± 0.3	5	21.2 ± 0.9	6	1.42	4.32	6.12	16.73	− 2.80	20	2	99
HIP 25486	F7	05:27:04	−11:54:04	17.1 ± 0.03	− 49.2 ± 0.02	5	37.4 ± 0.3	5	20.2 ± 0.5	29	0.53	1.37	4.93	12.86	− 3.53	162	28,14,25	100
HIP 27321	A5V	05:47:17	−51:03:59	4.7 ± 0.1	83.1 ± 0.2	27	51.4 ± 0.1	27	20.0 ± 0.7	7	0.16	0.32	3.53	–	–	0	2,25	100
HIP 29964	K4V	06:18:28	−72:02:43	− 7.7 ± 0.1	74.4 ± 0.1	5	25.6 ± 0.2	5	16.2 ± 1.0	16	1.07	3.18	6.81	16.70	− 2.72	400	28,14,4,25,31	100
TWA 22 B	M6V	10:17:26	−53:54:26	− 175.8 ± 0.8	− 21.3 ± 0.8	24	57.0 ± 0.7	24	14.8 ± 2.1	24	1.73	6.27	7.69	19.55	− 2.89	580	19,22	100
TWA 22 A	M6V	10:17:26	−53:54:26	− 175.8 ± 0.8	− 21.3 ± 0.8	24	57.0 ± 0.7	24	14.8 ± 2.1	24	1.73	6.27	7.69	19.55	− 2.89	580	19,22	100
HIP 76629 BC	M4.5	15:38:56	−57:42:18	− 52.9	− 106.0	25	27.1 ± 0.3	5	0.1 ± 2.0	25	1.71	5.61	9.19	–	− 1.6	425	25,2,22	100
HIP 76629 A	K0V	15:38:57	−57:42:26	− 49.9 ± 0.06	− 97.9 ± 0.1	5	27.1 ± 0.3	5	3.1 ± 0.8	27	0.85	2.30	5.85	14.18	− 3.24	280	28,14,25,31	100
HIP 79881	A0	16:18:17	−28:36:51	− 31.2 ± 0.3	− 100.9 ± 0.2	27	24.2 ± 0.2	27	− 13.0 ± 0.8	7	0.02	0.04	4.74	–	–	0	32	99
HIP 84586 A	G5IV	17:17:25	−66:57:03	− 21.5 ± 0.02	− 137.3 ± 0.03	5	32.8 ± 0.4	5	5.9 ± 0.2	27	0.81	2.17	4.70	12.78	− 3.20	250	25	100
HIP 84586 B	K0IV	17:17:25	−66:57:03	− 21.5 ± 0.02	− 137.3 ± 0.03	5	32.8 ± 0.4	5	5.9 ± 0.2	27	0.81	2.17	4.70	12.78	− 3.20	250	25	100
HIP 84586 C	M3V	17:17:31	−66:57:05	− 11.0 ± 2.0	− 143.0 ± 2.0	30	32.8 ± 0.4	5	2.7 ± 1.8	25	1.54	5.19	7.63	–	− 1.45	20	2,25	100
HIP 86598	F9V	17:41:48	−50:43:28	− 3.7 ± 1.1	− 65.7 ± 0.9	27	13.8 ± 0.9	27	1.7 ± 1.7	23	0.55	1.37	6.99	–	− 3.64	130	9	85
HIP 88399 A	F5V	18:03:03	−51:38:54	2.3 ± 0.04	− 86.1 ± 0.03	5	19.8 ± 0.3	5	− 0.4 ± 0.5	27	0.43	1.10	5.91	–	− 4.53	107	25	100
HIP 88399 B	M2V	18:03:04	−51:38:56	2.3 ± 0.04	− 86.1 ± 0.03	5	19.8 ± 0.3	5	− 2.4 ± 1.3	25	1.52	4.23	8.27	–	− 2.93	70	25	100
HIP 88726 A	A5V	18:06:49	−43:25:30	10.7 ± 1.1	− 106.6 ± 0.5	30	23.9 ± 0.7	27	− 7.8 ± 0.4	7	0.22	0.55	4.39	–	–	0	11	100
HIP 88726 B	A5V	18:06:49	−43:25:29	10.7 ± 1.1	− 106.6 ± 0.5	30	23.9 ± 0.7	27	− 7.8 ± 0.4	7	0.24	0.55	4.39	–	–	0	11	100
HIP 89829	G5V	18:19:52	−29:16:32	4.6 ± 0.1	− 46.4 ± 0.1	5	12.6 ± 0.3	5	− 7.0 ± 2.6	25	0.64	1.75	7.05	–	− 3.23	290	2,25	88
HIP 92024 A	A7	18:45:26	−64:52:16	32.4 ± 0.2	− 149.5 ± 0.2	27	35.0 ± 0.2	27	2.0 ± 4.2	27	0.20	0.47	4.30	–	− 5.70	0	25	99
HIP 92024 BC	K7V	18:45:36	−64:51:45	25.9 ± 8.0	− 184.2 ± 8.0	30	35.0 ± 0.2	27	1.0 ± 3.0	25	1.12	3.30	6.10	–	− 2.98	477	14,25	98
HIP 92680	G9IV	18:53:05	−50:10:47	17.6 ± 1.1	− 83.6 ± 0.8	27	19.4 ± 1.0	27	− 4.2 ± 0.2	7	0.81	2.04	6.37	14.48	− 3.23	279	14,25	100
HIP 95270	F5.5	19:22:58	−54:32:15	24.5 ± 0.04	− 82.2 ± 0.03	5	20.6 ± 0.5	5	0.1 ± 0.4	7	0.46	1.13	5.91	–	–	117	28,14,25	100
HIP 99273	F5V	20:09:05	−26:13:26	40.4 ± 0.04	− 67.5 ± 0.03	5	19.6 ± 0.3	5	− 6.4 ± 1.7	3	0.44	1.10	6.08	12.07	− 4.90	95	2	100
HIP 102141 B	M4V	20:41:50	−32:26:10	286.2 ± 8.0	− 377.2 ± 8.0	30	93.5 ± 3.7	27	− 5.2	25	1.6	5.39	4.94	15.96	− 2.63	0	25	100
HIP 102141 A	M4V	20:41:51	−32:26:07	270.5 ± 4.6	− 365.6 ± 3.5	27	93.5 ± 3.7	27	− 3.7 ± 3.0	15	1.55	5.39	4.94	15.96	− 2.63	0	25	100
HIP 102409	M1V	20:45:09	−31:20:27	281.4 ± 0.1	− 360.1 ± 0.04	5	102.1 ± 0.4	5	− 4.5 ± 0.3	1	1.45	4.23	4.53	15.61	− 2.77	68	28,14,25	100
HIP 103311 AB	F8V	20:55:47	−17:06:51	58.8 ± 0.8	− 62.8 ± 0.7	27	21.9 ± 0.8	27	− 4.5 ± 2.1	25	0.52	1.51	5.81	–	− 3.41	110	28,25,8	100
HIP 112312 A	M4IV	22:44:57	−33:15:02	179.9 ± 0.2	− 123.3 ± 0.1	5	48.2 ± 0.6	5	3.2 ± 0.5	20	1.52	5.14	6.93	18.26	− 2.36	0	21,25	100
HIP 112312 B	M5IV	22:45:00	−33:15:26	171.1 ± 1.3	− 125.2 ± 4.3	30	48.2 ± 0.6	5	2.0 ± 5.2	10	1.60	5.56	7.79	19.77	− 2.22	336	14,4,25,26	100

Table 5 – *continued*

Name	SpT.	R.A. (hh:mm:ss)	Dec. (dd:mm:ss)	μ_α (mas yr^{-1})	μ_δ (mas yr^{-1})	μ Ref.	π (mas)	π Ref.	RV (km s^{-1})	RV Ref.	$B-V$ (mag)	$V-K$ (mag)	K (mag)	NUV (mag)	$\log L_X/L_{bol}$	Li[a] (mÅ)	Li Ref.	p(BPMG)[b] (per cent)
Newly confirmed members																		
2MASS J00172353−6645124	M2.5	00:17:24	−66:45:13	102.9 ± 1.0	− 15.0 ± 1.0	30	25.6 ± 1.7	17	10.8 ± 0.2	12	1.54	4.65	7.70	19.12	− 3.00	–	–	100
GJ 2006 A	M4	00:27:50	−32:33:06	99.2 ± 1.3	− 61.3 ± 2.6	30	30.1 ± 2.5	17	9.5 ± 0.3	11	1.38	4.94	8.01	19.48	− 2.18	–	–	100
GJ 2006 B	M3.5	00:27:50	−32:33:24	117.2 ± 4.1	− 31.5 ± 5.8	30	31.8 ± 2.5	17	8.5 ± 0.2	12	1.41	5.13	8.12	18.87	− 2.20	–	–	100
2MASS J16572029−5343316	M3	16:57:20	−53:43:32	− 13.0 ± 6.3	− 85.1 ± 2.2	30	19.4 ± 0.7	5	1.4 ± 0.2	12	1.46	4.62	7.79	–	− 3.23	–	–	100
CD-54 7336	K1V	17:29:55	−54:15:49	− 9.8 ± 3.2	− 60.0 ± 1.7	30	14.4 ± 0.2	5	− 0.2 ± 0.9	3	0.77	2.25	7.36	–	− 3.13	360	2,25	97
CD-31 16041	K8V	18:50:44	−31:47:47	16.4 ± 1.6	− 72.8 ± 1.1	30	20.1 ± 0.3	5	− 6.0 ± 1.0	25	1.06	3.73	7.46	18.04	− 2.79	492	2,25	100
TYC 7443-1102-1	K9IV	19:56:04	−32:07:38	31.9 ± 1.4	− 65.1 ± 1.2	30	19.9 ± 0.3	5	− 7.1 ± 2.2	10	1.36	3.74	7.85	19.09	− 2.89	110	13,9	99
UCAC3 124−580676	M3	20:10:00	−28:01:41	40.7 ± 3.0	− 62.0 ± 1.7	30	20.9 ± 1.3	17	− 5.8 ± 0.6	12	1.50	5.26	7.73	18.43	− 2.66	–	–	99
2MASS J20333759−2556521	M4.5	20:33:38	−25:56:52	52.8 ± 1.7	− 75.9 ± 1.3	30	20.7 ± 1.4	17	− 6.0 ± 0.5	12	1.71	5.99	8.88	20.25	− 3.04	–	–	100
2MASS J21212873−6655063	K7V	21:21:29	−66:55:06	97.2 ± 1.1	− 104.1 ± 1.6	30	31.1 ± 0.8	5	3.3	25	1.34	3.59	7.01	–	− 2.92	15	25	100
CPD-72 2713	K7V	22:42:49	−71:42:21	92.7 ± 0.8	− 51.1 ± 0.8	30	27.4 ± 0.3	5	8.6 ± 0.5	25	1.32	3.67	6.89	17.55	− 2.80	440	2,25	100
BD-13 6424	M0V	23:32:31	−12:15:51	137.4 ± 1.0	− 81.0 ± 1.0	30	36.0 ± 0.5	5	1.8 ± 0.7	25	1.74	4.07	6.57	17.82	− 3.68	185	2,25	100
Probable members																		
Group 1: young, but missing π or RV																		
GSC 08350−01924	M3V	17:29:21	−50:14:53	− 5.8 ± 1.5	− 62.7 ± 5.1	30	–	–	0.3 ± 1.1	12	1.46	4.87	7.99	–	− 2.94	50	2	88
HD 161460	K0IV	17:48:34	−53:06:43	− 3.6 ± 1.0	− 58.4 ± 1.3	30	–	–	− 0.2 ± 1.5	23	0.97	2.31	6.78	–	− 3.14	320	2,25	89
Smethells 20	M1V	18:46:53	−62:10:37	13.6 ± 1.4	− 79.4 ± 1.4	30	–	–	0.3 ± 3.2	10	1.24	3.98	7.85	–	− 3.00	332	2,25	97
AZ Cap	K7	20:56:03	−17:10:54	57.6 ± 1.1	− 59.9 ± 1.2	30	–	–	− 6.9	25	1.12	3.44	7.04	–	− 3.25	235.5	25,14	99
Group 2: probably young, but missing π or RV																		
2MASS J00281434−3227556	M5	00:28:14	−32:27:56	110.1 ± 1.8	− 43.0 ± 3.3	30	–	–	5.9 ± 3.4	12	1.58	5.95	9.28	20.85	− 2.55	–	–	89
PYC J00390+1330	M4	00:39:03	+13:30:17	85.5 ± 3.2	− 68.0 ± 3.9	30	–	–	–	–	1.60	5.64	10.06	21.29	− 2.74	–	–	97
BD+17 232A	–	01:37:39	+18:35:33	68.6 ± 0.8	− 47.3 ± 0.6	30	–	–	3.2 ± 1.0	18	1.03	3.86	6.72	14.37	− 2.62	–	–	97
UCAC3 176−23654	M3	05:34:00	−02:21:32	12.3 ± 1.2	− 61.3 ± 2.4	30	–	–	21.0 ± 0.2	12	1.49	4.72	7.70	–	− 2.57	0	32	96
2MASS J08173943−8243298	M3.5	08:17:39	−82:43:30	− 80.3 ± 1.1	102.5 ± 0.8	30	–	–	17.5 ± 1.6	12	1.58	5.03	6.59	17.59	− 2.94	0	32	94
UPM J1354−7121	M2.5	13:54:54	−71:21:48	− 165.0 ± 8.0	− 132.7 ± 8.0	30	–	–	5.7 ± 0.2	12	1.48	4.57	7.67	18.53	− 3.10	–	–	100
2MASS J17150219−3333398	M0	17:15:02	−33:33:40	7.8 ± 1.0	− 175.9 ± 1.2	30	–	–	− 14.6 ± 3.5	12	1.41	3.87	7.07	–	− 2.99	–	–	87
2MASS J18420694−5554254	M3.5	18:42:07	−55:54:26	9.7 ± 12.1	− 81.2 ± 2.8	30	–	–	0.3 ± 0.5	12	1.58	4.95	8.58	19.70	− 2.72	0	32	98
2MASS J19102820−2319486	M4	19:10:28	−23:19:49	16.6 ± 1.4	− 51.8 ± 1.4	30	–	–	− 8.0 ± 0.8	12	1.53	5.01	8.21	19.08	− 2.69	–	–	86
2MASS J19243494−3442392	M4	19:24:35	−34:42:39	22.1 ± 1.8	− 71.7 ± 1.8	30	–	–	− 3.2 ± 0.3	12	1.58	5.52	8.79	20.00	− 3.11	–	–	94
UCAC3 116−474938	M4	19:56:03	−32:07:19	35.2 ± 1.8	− 59.9 ± 1.5	30	–	–	− 2.8 ± 1.8	12	1.56	5.12	8.1	19.60	− 2.73	0	9	81
GSC 06354−00357	M2	21:10:05	−19:19:57	89.0 ± 0.9	− 89.9 ± 1.8	30	–	–	− 5.5 ± 0.5	12	1.52	4.46	7.20	18.58	− 2.83	–	–	100
Group 3: young with full six kinematic parameters, but low membership probability																		
TYC 6872-1011-1	M0V	18:58:04	−29:53:05	12.2 ± 1.3	− 45.7 ± 2.5	30	12.8 ± 0.4	5	− 4.9 ± 1.0	25	2.16	3.78	8.02	–	–	483	2,25	60

Notes. [a]K_s magnitudes from the Two Micron All-Sky Survey (Cutri et al. 2003).
[b]Near-UV magnitudes in the GALEX fifth data release (Bianchi et al. 2011).
[c]X-ray–to–bolometric flux ratios. X-ray data are from ROSAT All-Sky point source datalogue (Voges et al. 1999, 2000).
[d]If multiple data are available, weighted mean is used.
[e]The membership probability for BPMG is calculated using the improved models (the new field star model and uniformly distributed BPMG model in XYZ using *Exclusive list–Case V*).
Notes. References to the table: (1) Chubak & Marcy (2011); (2) da Silva et al. (2009); (3) Desidera et al. (2015); (4) Fernàndez, Figueras & Torra (2008); (5) Gaia Collaboration (2016); (6) Gizis, Reid & Hawley (2002); (7) Goncharov (2006); (8) Kaiser et al. (2004); (9) Kiss et al. (2011); (10) Kordopatis et al. (2013); (11) Kraus et al. (2014); (12) Malo et al. (2014); (13) McCarthy & White (2012); (14) Mentuch et al. (2008); (15) Montes et al. (2001b); (16) Montes et al. (2001a); (17) Riedel et al. (2014); (18) Schlieder et al. (2010); (19) Shkolnik et al. (2011); (20) Shkolnik et al. (2012); (21) Song, Bessell & Zuckerman (2002); (22) Song et al. (2003); (23) Song et al. (2012); (24) Teixeira et al. (2009); (25) Torres et al. (2006); (26) van Altena, Lee & Hoffleit (1995); (27) van Leeuwen (2007); (28) Weise et al. (2010); (29) White, Gabor & Hillenbrand (2007); (30) Zacharias et al. (2013); (31) Zuckerman et al. (2001b); (32) Internel data.

A single star in Group 3, TYC 6872-1011-1, has the full six kinematic parameters showing unambiguous youth, but its kinematic probability is slightly low (∼60 per cent). This star was also suggested to be a BPMG member in several studies (Torres et al. 2006; Messina et al. 2010; Malo et al. 2013, 2014).

3.2.5 *Summary*

Among all 275 BPMG candidate members in the *SIMBAD list*, 57 stars can be confirmed as bona fide BPMG members. 39 stars are from the *BANYAN II list*, and 12 stars are newly confirmed. We additionally include traditional six BPMG members showing ambiguity in youth. These stars should be removed in the future if they show clear evidence of non-memberships. Five stars from the *BANYAN II list* are rejected, mainly due to updated low kinematic membership probabilities. We note that some of the false members were used in several age-related studies (e.g. absolute isochronal age scale, Bell, Mamajek & Naylor 2015; lithium depletion boundary age, Bink & Jeffries 2016), which could have biased the results.

The list of updated bona fide members was utilized to revise a BPMG model ($BPMG_{revised}$ in Table 3), which, in turn, can be used in future searches for members based on new data from the *Gaia* mission.

4 SUMMARY AND CONCLUSIONS

Deploying the same formulation that BANYAN II used, we examine the impact of three assumptions on models in the MG membership probability calculation: accepted initial member lists, distribution models of MG members, and distribution models of field stars. Reassessment of membership of BPMG members in the *BANYAN II list* results in a refined kinematic model for BPMG. Depending on the membership assessment criteria (exclusive and inclusive), membership probabilities of stars in a test set (the *SIMBAD list*) change up to ∼40 per cent. Lacking evidence of a central concentration of BPMG members in *XYZ*, we suggest to use the uniform distribution model in *XYZ*. This uniform spatial distribution model changes the membership probabilities of the test stars up to ∼80 per cent compared to the Gaussian distribution. For field star models, assuming the uniform distribution in *XYZ* is more realistic compared to the Gaussian distribution model; the uniform distribution model expects more field stars at larger distance, while the Gaussian model expects the maximum stellar number density at ∼120 pc, which seems to be artificial. In *UVW*, field stars show distinct subgroups, and the model properties of these subgroups are obtained using a Gaussian mixture model. Combined effect of these model modifications show changes in membership probabilities of the test stars up to ∼80 per cent. These comparisons show significant membership probability changes especially for some marginal members, indicating the sensitivity to prior knowledge on the MG membership calculation and the importance of using reliable models.

We confirm 57 (51, if we exclude six classical members showing ambiguity in youth) BPMG members from the *SIMBAD list*. Only about 90 stars from the *SIMBAD list* seem to be kinematically associated with BPMG ($p > 80$ per cent), and 51 (12 stars are new compared to the *BANYAN II list*) out of these ∼90 stars show unambiguous signs of youth with six full kinematic parameters, which allow us to confirm them as bona fide BPMG members. Additionally, we suggest 17 probable BPMG members.

In this study, we considered only kinematic properties in the MG membership probability calculation. Because the number density of field stars is much larger than those of MG members and there are many field stars with similar *UVW* to that of MGs, the contamination (old interlopers) rate has to be significantly large without considering age-related information. In the future, we will formally incorporate the age-related information into the Bayesian scheme developed in this study to provide a more reliable MG membership calculation (Lee & Song in preparation).

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