A search for new members of the $\beta$ Pic, Tuc-Hor and $\epsilon$ Cha moving groups in the RAVE database

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ABSTRACT
We report on the discovery of new members of nearby young moving groups, exploiting the full power of combining the RAVE survey with several stellar age diagnostic methods and follow-up high-resolution optical spectroscopy. The results include the identification of one new and five likely members of the $\beta$ Pictoris moving group, ranging from spectral types F9 to M4 with the majority being M dwarfs, one K7 likely member of the $\epsilon$ Cha group and two stars in the Tuc-Hor association. Based on the positive identifications we foreshadow a great potential of the RAVE database in progressing toward a full census of young moving groups in the solar neighbourhood.

Key words: stars: kinematics – open clusters and associations: individual: $\beta$ Pictoris moving group, Tucana-Horologium association, $\epsilon$ Cha association.

1 INTRODUCTION
In the last decade many young (<100 Myr) stars have been identified in the solar neighbourhood. Most of them belong to different moving groups, in which stars share
common age and motion through the Galaxy (for review see Zuckerman & Song 2004). Up to now nine such kinematic assemblages have been revealed within 150 pc of our Solar System with ages ranging from 8 Myr to 70 Myr (Torres et al. 2008), most situated in the southern hemisphere far from known star forming regions. However, tracing back their space trajectories shows that the birthplace of some of them may have been close to the nearest sites of massive star formation, the Sco-Cen region (Fernández, Figueras & Torra 2008).

Young moving groups are rich in debris discs, which implies very active planetesimal formation around these stars (Moor et al. 2008; Rebull et al. 2008). Since the epochs of several key events in the early Solar System (e.g. formation of terrestrial planets, Apai 2009) overlap well with the age of these groups, discs around the members are favourable and so present nearby and well-dated sites for investigations of planet formation and evolution. The members are also ideal targets when one would like to detect sub-stellar objects via direct imaging, since giant gas planets are thought to fade significantly during their evolution (e.g. Kasper et al. 2007).

Most of the known young stellar kinematic groups occupy a large area on the sky (up to thousands of square degrees), which makes the identification of members very difficult. However, by combining astrometric data with radial velocity information and by applying relevant age diagnostical methods, one can search for additional members of known groups or reveal new kinematic assemblages. Using this approach, recent studies revealed more than 300 young stars belonging to nine kinematic groups in the vicinity of our Sun (Torres et al. 2008). It is clear, however, that the census of these groups is far from complete, because of the lack of necessary kinematic information – particularly the radial velocities and the trigonometric distances – for most of the stars. For example, comparing the list of members with the 6dF multi-object spectrograph. The project has already resulted in two data releases (Steinmetz et al. 2006; Makarov 2007; Mentuch et al. 2008; da Silva et al. 2009), at present the mostly approved value is 30 Myr (Torres et al. 2008). The ε Cha association may be the youngest among the three selected assemblages. Its age estimates range between 3 Myr and 15 Myr (Terranegra et al. 1999; Feigelson, Lawson, & Garnire 2003; Jilinski, Ortega, & de la Reza 2003; Torres et al. 2008), most cases below 7 Myr. We used strict criteria to select potential candidates and then the RAVE-based list was supplemented by some additional stars taken primarily from the Hipparcos catalogue (Sect. 2). In order to confirm the membership of our candidates we performed follow-up high-resolution spectroscopy (Sect. 3). The final assignments of the candidate stars are summarised in Sect. 4, with concluding remarks in Sect. 5.

2 SAMPLE SELECTION

2.1 Search in the RAVE catalogue

The RAVE sample was examined in the U, V, W, X, Y, Z space, defined by the heliocentric space motion (U,V,W) and the physical space coordinates centred on the Sun (X,Y,Z). The computation of these parameters for a star requires knowledge of its coordinates, proper motion, radial velocity and distance. While coordinates (right ascension, declination), proper motion (in right ascension and in declination) and radial velocity information could be taken from the RAVE catalogue, for most of the RAVE stars no trigonometric distances were available. Therefore, the U,V,W,X,Y,Z values were calculated for a range of distances, between 5 pc and 120 pc with a resolution of 1 pc, to check whether any distance resulted in a coordinate which coincided with the region of a specific association in this 6-dimension space. In those cases where a RAVE star has a trigonometric parallax, measured by Hipparcos (van Leeuwen 2007), we used that value in the computations. The search was limited for those stars whose proper motion measurement fulfills the following criteria 1) \( \mu = \sqrt{\mu_\alpha^2 + \mu_\delta^2} > 20 \text{mas yr}^{-1} \) and 2) \( \mu / \sigma_\mu > 5 \).

The characteristic space motion (\( U_0, V_0, W_0 \)) of the groups were taken from Torres et al. (2008). We selected those objects from the RAVE catalogue, where \( \min((U - U_0)^2 + (V - V_0)^2 + (W - W_0)^2)^{1/2} < 4 \text{ km s}^{-1} \). The chosen limit corresponds to the internal dispersion of the known
members of the groups, while the distance resulting the minimum value was adopted as the kinematic distance to the object. For the β Pic moving group (hereafter BPMG), Torres et al. (2006) found a correlation between the U component of the Galactic space motion and the X space coordinate. Using this method we compiled a region limited by the known members of the groups (Torres et al. 2008). Using this method we compiled an initial list of stars, that includes 3 ECA, 803 BPMG and 62 THA candidate members.

The initial lists were further evaluated and filtered: 1) placing our candidates in the colour-magnitude diagrams of the specific kinematic groups; and 2) by searching for X-ray counterparts in the ROSAT catalogues (Voges et al. 1999, 2000). We selected only those targets whose fractional X-ray luminosities (L_x/Lbol) and position in the colour-magnitude diagram were consistent with the similar properties of the known members (see Fig. 1h–d). Our procedure finally resulted in 2, 9 and 7 candidate members of the ϵ Cha, BPMG and THA groups, respectively. By searching the literature we revealed that ten of our candidates (1 ϵ Cha, 4 BPMG and 5 THA stars) are already known members. Moreover, one of our THA candidate, J042110.3-243221 (HD 27679), has already assigned to the Columba moving group by Torres et al. (2008), while one of the BPMG candidate (TYC 7558-655-1) has an ambiguous assignment in the literature. Torres et al. (2008) identified TYC 7558-655-1 as a possible member of the Columba group, on the other hand Schlieder, Lépine, & Simon (2010) proposed that this star likely belongs to the BPMG. We omitted these known/ambiguous members from the further observations and analysis. Thus, we finally selected six RAVE candidates (1 ϵ Cha, 4 BPMG and 1 THA stars) for further investigations. These RAVE-based candidate list was supplemented by one additional star, J19560294-3207186, that is the comoving pair of one of new candidate object (TYC 7443-1102-1).

2.2 Search in the HIPPARCOS catalogue

The Hipparcos catalogue was also searched for additional candidate members. Similarly to the RAVE sample, the Hipparcos stars were also examined in the U, V, W, X, Y, Z space. Here the radial velocity data are lacking for a significant fraction of stars, therefore the U, V, W values were calculated for a range of radial velocities (radial velocity values were varied between $-50$ km s$^{-1}$ and $+50$ km s$^{-1}$ with a resolution of $0.5$ km s$^{-1}$). For those stars where radial velocity data were available in the literature (Famaey et al. 2005; Moór et al. 2006; Gontcharov 2006; Torres et al. 2008; Holmberg, Nordström, & Andersen 2007; Kharchenko et al. 2007) we used the measured value in the computation. The search was limited to stars with spectral type later than F8. In the selection of candidate stars we applied almost identical criteria as in the case of RAVE objects. The only change in the method was related to those stars where all six parameters are available, thus U, V, W, X, Y, Z could be computed without any assumption, where we utilized a weaker criterion concerning to the X-ray luminosity of the object: we retained those candidates too where the upper limit of the X-ray luminosity was consistent with the similar property of the known members. Using this method in the BPMG we could recover – with the exception of HIP 10679 – all known members that are quoted in Hipparcos (and has spectral type F8 or later). We note that HIP 10679 comprises a binary system with HIP 10680 and the latter object has been successfully recovered by our method. Moreover, HIP 10679 could be also recovered when we applied the more accurate trigonometric parallax of HIP 10680 for this star as well. Three new candidate stars, HD 37144, HD 160305 and HD 190102, have been revealed. For HD 37144 and HD 190102 radial velocity data and lithium equivalent widths measured in the framework of the SACY survey (Torres et al. 2006) have already been available. Although the kinematic parameters fulfilled our criteria, the low values of the lithium equivalent widths did not confirm their membership. Based on similar considerations, da Silva et al. (2009) also rejected HD 190102 as a member of BPMG. For HD 160305 no radial velocity or lithium data were found in the literature, thus this object was added to the list of candidates. For THA and ECA we recovered all known members included in the Hipparcos catalogue. As a result of our search we revealed one new THA candidate, HD 25402, for which radial velocity was available in the catalogue of Holmberg, Nordström, & Andersen (2007). Since its computed kinematic parameters correspond well to the characteristic values of THA we added this candidate to our list.

3 OBSERVATIONS AND DATA REDUCTION

We have obtained new high-resolution optical spectroscopy for all stars in Table 1 on six nights in July 2009 and three nights in August 2009, using the 2.3-m telescope and the Echelle spectrograph of the Australian National University. The total integration time per object ranged from 30 s to 1800 s, depending on the target brightness. The spectra covered the whole visual range in 27 echelle orders between 3900 Å and 6720 Å with only small gaps between the three reddest orders. The nominal spectral resolution is $\lambda/\Delta\lambda \approx 23 000$ at the Hα line, with typical signal-to-noise ratios of about 100 (for the faintest red dwarf stars the blue parts of the spectra were much noisier).

All data were reduced with standard IRAF tasks, including bias and flat-field corrections, cosmic ray removal, extraction of the 27 individual orders of the echelle spectra, wavelength calibration, and continuum normalization. ThAr spectral lamp exposures were regularly taken before and after every object spectrum to monitor the wavelength shifts of the spectra on the CCD. We also obtained spectra for the telluric standard HD 177724 and IAU radial velocity (RV) standards β Vir (sp. type F9V) and HD 223311 (K4III).

The spectroscopic data analysis consisted of two main steps. First, we measured radial velocities (RVs) by cross-correlating the target spectra (using the IRAF task fxcor)
with that of the RV standard that matched the spectral type of the target – β Vir was used for the early-type targets (A– F–mid-G), HD 223311 for the late-type ones (late-G–K–M). Each spectral order was treated separately and the resulting velocities and the estimated uncertainties were calculated as the means and the standard deviations of the velocities from the individual orders. For most of the targets, the two IAU standards yielded RVs within 0.1–0.5 km s\(^{-1}\), which is an independent measure of the absolute uncertainties. Using the new, more accurate RV data we recomputed the U, V, W values of its companion (TYC catalogue. For J19560294-3207186, we adopted the kinematic distances and proper motions were taken from the Hipparcos catalogue. For HD25402 and HD 160305, distances were taken from the Hipparcos catalogue, otherwise we used kinematic distances (in parentheses). The typical uncertainty of the kinematic distances is estimated to be \(\sim 10\%\), based on a comparison between the kinematic and trigonometric distances of known members of BPMG and THA. The estimated uncertainty of the U,V,W components is about 1-2 km s\(^{-1}\).

### Table 1. Properties of the candidate stars. References for spectral types: 1 - Riaz, Gizis, & Harvin (2006); 2 - Hipparcos catalogue; 3 - López & Simon (2009); 4 - this paper, based on V–K\(_s\). For HD 25402 and HD 160305, distances were taken from the Hipparcos catalogue, otherwise we used kinematic distances (in parentheses). The typical uncertainty of the kinematic distances is estimated to be \(\sim 10\%\), based on a comparison between the kinematic and trigonometric distances of known members of BPMG and THA. The estimated uncertainty of the U,V,W components is about 1-2 km s\(^{-1}\).

| Source ID | RA (2000) | DEC (2000) | SpT. | V | K\(_s\) | D | \(v_{\text{rad}}\) | U, V, W | EW\(_L\) | EW\(_H\) | \(\log \alpha_{\text{hel}}\) |
|-----------|-----------|-------------|------|---|--------|---|----------------|----------|---------|---------|------------|
| J12210499-7116493 | 12 21 05.00 | -71 16 49.3 | K7\(^1\) | candidate \(\epsilon\) Cha group members | 12.16 | 8.24 | 0.98 | +8.1±0.6 | [−11.8,−17.9,−8.8] | 0.550±0.020 | −0.80±0.02 | −2.99 |
| J01071194-1935359 | 01 07 11.94 | -19 35 36.0 | M1\(^1\) | candidate \(\beta\) Pic moving group members | 11.41 | 7.25 | 0.54 | +11.5±1.4 | [−8.6,−16.9,−8.3] | 0.302±0.005 | −2.00±0.05 | −3.13 |
| J16430128-1754274 | 16 43 01.33 | -17 54 26.9 | M0.5\(^1\) | | 12.63 | 8.55 | 0.57 | −13.0±4.0 | [−11.5,−16.0,−6.6] | 0.300±0.020 | −2.50±0.10 | −3.13 |
| HD160305 | 17 41 49.04 | -50 43 28.1 | F9V\(^2\) | | 8.35 | 6.99 | 0.72 | +2.4±1.1 | [−6.1,−19.2,−10.5] | 0.139±0.040 | 2.60±0.40 | −3.67 |
| J19560294-3207186 | 19 56 02.94 | -32 07 18.7 | M4\(^1\) | | 13.30 | 8.11 | 0.56 | −11.0±5.0 | [−9.8,−16.3,−8.1] | <0.100 | −4.50±0.10 | −2.91 |
| TYC 7443-1102-1 | 19 56 04.37 | -32 07 37.7 | M0\(^3\) | | 11.80 | 7.85 | 0.56 | −7.2±0.4 | [−9.8,−16.3,−8.1] | 0.101±0.020 | −0.68±0.04 | <−3.47 |
| J20013718-3313139 | 20 01 37.18 | -33 13 14.0 | M1\(^1\) | candidate Tucana-Horologium association members | 12.25 | 8.24 | 0.62 | −5.6±1.8 | [−8.7,−16.5,−8.3] | <0.100 | −1.03±0.07 | −3.39 |
| J01521830-5950168 | 01 52 18.29 | -59 50 16.8 | M2-3\(^4\) | | 12.94 | 8.14 | 0.39 | +7.9±1.6 | [−10.2,−19.5,0.7] | <0.020 | −2.30±0.10 | −3.16 |
| HD25402 | 04 00 31.99 | -41 44 54.4 | G1V\(^2\) | | 8.40 | 6.88 | 0.48 | +16.3±0.7 | [−9.1,−20.9,−1.7] | 0.145±0.005 | +2.20±0.30 | <−4.02 |

### 4 RESULTS

Though stars in a specific group can be widely scattered across the sky, their common properties offer an opportunity to identify other members in the field by prescribing that a candidate must have similar space motion, as well as age, to the known members. The age criterion is essential because there may be a non-negligible fraction of old field stars which have similar space motion to the young group members (Zuckerman & Song 2004; López-Santiago, Micela, & Montes 2009).

Using the new RV data we recomputed the U, V, W values for each candidate star and compared the values with the characteristic space motion (U\(_0\), V\(_0\), W\(_0\)) of the corresponding kinematic groups. Apart from HD 25402 and HD 160305, we used kinematic distances and the proper motion data were taken from the UCAC3 catalogue (Zacharias et al. 2010) for all of our targets. For HD 25402 and HD 160305, distances and proper motions were taken from the Hipparcos catalogue. For J19560294-3207186, we adopted the kinematic distance and U, V, W values of its companion (TYC 7443-1102-1). We required \(\sqrt{(U−U_0)^2+(V−V_0)^2+(W−W_0)^2}/2 < 4 \text{ km s}^{-1}\) for the group membership. This criterion was fulfilled for all candidate stars, i.e. none of the refined RV data resulted in a deprived candidacy.

We used three different age diagnostic methods to evaluate whether the candidates are approximately coeval with the corresponding kinematic groups. In all age indicators we compared the specific properties of the candidates stars to the corresponding properties of the known members with similar colour indices.

Figure 1a,b,c show the colour-magnitude diagrams (M\(_K\) vs. V–K\(_s\)) of the ECA, BPMG and THA groups. The lists of known group members are from Torres et al. (2008), which have then been queried in the Hipparcos and 2MASS databases to produce Fig. 1a,b,c. Candidate members are plotted with different symbols in the corresponding panels, showing that they indeed occupy a distinct region in the CMD. Since in these young groups a significant fraction of the stars are in pre-main sequence evolutionary stage, the characteristic loci of the members in the CMD deviate from the position of the main-sequence stars, which helps filter out spurious (old) candidates. The younger the association the higher the deviation, because more and more massive stars are still in pre-main sequence stage.

Young stars are also known to have enhanced coronal activity with strong X-ray emission making the latter property a good indicator of youth. We have cross-correlated the list of the candidates and known members of the three groups with the ROSAT All-Sky Survey catalogues (Voges et al. 1999, 2000). We selected only those objects where the match between the optical and X-ray positions was within 40\(^\prime\). In all of the positive matches we checked the DSS images to evaluate whether there are any other nearby sources of X-ray emission within the ROSAT positional uncertainties. The X-ray fluxes of the sources were computed using the count rate to-energy flux conversion formula by Schmitt et al. (1995). For those two objects where no X-ray counterparts were found we utilized the ROSAT All-Sky survey images to derive an upper limit in the X-ray flux. Figure 1d displays the fractional X-ray luminosities vs. V–K\(_s\) for the group members and the candidate stars. The ROSAT X-ray hardness ratios (HR1 and HR2) of the X-ray counterparts were also plotted in an inset of Fig. 1d. Analyzing the ROSAT hardness ratio values (HR1 and HR2) for T Tauri stars, young moving group members and for old field stars, Kastner et al. (2003) demonstrated that the X-ray spectra of F through M stars soften with age. They ar-
New members of young moving groups

Figure 1. Upper panels: Absolute $K_s$ magnitude versus $V-K_s$ colour diagrams for the known and candidates members of ECA (panel a), BPMG (panel b) and THA (panel c) kinematic groups. Following Lépine & Simon (2009), the loci of the known members of the specific groups were fitted by a line, the ±1 magnitude range of the fitted loci are denoted by dotted lines in a–c panels. Nearly all known members are located within these lines in the diagrams. Candidate objects out of these area were omitted from our survey (see Sect. 2).

Panel d: Fractional X-ray luminosities as a function of $V-K_s$ for the known and candidates members of the three kinematic groups. The inset shows the X-ray hardness ratio HR1 vs. hardness ratio HR2 for the same objects. Large purple and blue diamonds show the characteristic hardness values for T Tauri stars and old K- and M-type main-sequence field stars, respectively. The characteristic values were taken from Kastner et al. (2003). The inset does not cover any symbol of the large panel.

Panel e: Equivalent width of Li $\lambda$6707.76 as a function of $V-K_s$. In all panels known members of BPMG, THA and ECA are plotted as black circles, black plus signs and black triangles, respectively. Squares denote those known close binaries where no photometric data are available separately for the individual components. Upper limits are displayed with down arrows.

Lithium is burned at low temperatures ($2.5 \times 10^6$ K) in stellar interiors. Since lithium is destroyed and never created in nuclear reactions, primordial lithium depletes monotonically with time in stars with a convective layer. It makes lithium one of the best age indicators for young stars (Zuckerman & Song 2004). The measured lithium equivalent widths of the candidates (from Table 1), as well as the known group members are plotted in Figure 1e as a function of $V-K_s$. For known group members the lithium data were taken from different surveys (Torres et al. 2006; da Silva et al. 2009).

In tight binaries the tidal interactions can induce strong activity indicating a spurious young age even if the system is old otherwise. Thus these ratios can also be used to discriminate between young and old stars.

Our high-resolution spectra allowed us to search for double- and multilined binaries by cross-correlating with the IAU RV standards. We found no double-lined binaries among our sample stars. Apart from HD 160305 – where no previous RV data were available – velocities measured by us all agree well with those in the RAVE data or published by Holmberg, Nordström, & Andersen (2007). Thus currently there is no evidence to suggest that any of our candidates reside in a tight multiple system.

4.1 Final assignment of candidate stars

Unfortunately, we have parallax information only for two of our candidates (HD 25402 and HD 160305). The lack of reliable trigonometric distances for RAVE stars makes the identification of new members ambiguous, even in those cases where the age diagnostic methods confirm the youth of the objects, because we cannot completely exclude the possibility that we observe a young star whose kinematic properties also lead to the estimates of spurious stellar parameters.
deviate from those of the moving group because its real distance deviate from the one we predicted using our method. Thus the RAVE-based candidates – in accordance with the nomenclature proposed by Schlesier, Lépine, & Simon (2010) – are classified as likely new members even in those cases when all of the prescribed membership criteria are fulfilled.

J12210499-7116493: Its position coincides well with the known members of ECA in all age diagnostic figures (Fig. 1(a)), The star has a somewhat larger HR1 ratio than most of the young group members, similar to the classical T Tauri star MP Mus recently assigned to ECA by Torres et al. (2008). Kastner et al. (2003) proposed that for T Tauri stars the presence of star-disc interaction and especially accretion can explain the stronger X-ray hardness ratios. Using the empirical criterion proposed by Barrado y Navascués & Martín (2003) to distinguish between stars with chromospheric activity and objects with accretion we conclude that the weak Hα emission of J12210499-7116493 (see Table 1) may be of chromospheric origin. Based on photometric data from ASAS3, Bernhard, Bernhard, & Bernhard (2009) found J12210499-7116493 to be a probable BY Dra type variable star with a period of 6.855 days. Since the properties of J12210499-7116493 to be a probable BY Dra type variable star with a period of 6.855 days. Since the properties of J12210499-7116493 fulfilled all of our criteria we propose it is a likely new member of ECA.

J01071104-1935359 and J16430128-1754274: All three age determination methods confirm that these stars are likely to be coeval with the BPMG. Although their spatial location somewhat deviate from the location of the known members, we classify both stars as likely new members of the BPMG.

HD 160305: This star is located quite close to three other BPMG stars (GSC 8350-1924, CD-54 7336, HD 161460), all within a sphere of 14 pc across. The position of the star in the age diagnostic diagrams is in good accordance with the known members of BPMG, hence we identify HD 160305 as a new member of the BPMG.

J19560294-3207186, TYC 7443-1102-1 and J20013718-3313139: Lépine & Simon (2009) proposed that TYC 7443-1102-1 and J20013718-3313139 are in good agreement with the corresponding astrometric properties of TYC 7443-1102-1 (μα, cos δ = 30.3 ± 1.5 mas, μδ = 66.6 ± 1.0 mas, vrad = −7.2±0.4 km s⁻¹). The derived kinematic distance of J19560294-3207186 is also close to that of TYC 7443-1102-1. We note that all three stars overlap well with the space distribution of previously known BPMG members. Even if J20013718-3313139 and TYC 7443-1102-1/J19560294-3207186 do not form a bound system, the stars are likely to be co-eval, therefore we can combine the results of different age diagnostic methods for the three objects. The absolute magnitudes and the X-ray fractional luminosities (only an upper limit for TYC 7443-1102-1) overlap well with the locus of known BPMG members in the CMD (Fig. 1(d)). 5 CONCLUSION

We searched for new members of three young kinematic assemblages (β Pic moving group, ε Cha and Tucana-Horologium associations) by combining radial velocity data from the RAVE survey with other astrometric information. We used strict selection criteria to filter out false candidates by requiring consistency with the colour-magnitude relationship and X-ray properties of the known members. In addition to recovering 10 known members of the three groups, we identified seven late-type (K,M) new candidates. This list was supplemented by two additional member candidates, HD 25402 and HD 160305, that were selected from the Hipparcos catalogue.

Utilizing our new high-resolution spectroscopic observations we found further pieces of evidence for the membership of our targets. As a result, we identified two new members (1 BPMG, 1 THA) and seven likely members (1 ECA, 5 BPMG, 1 THA) of the groups. All stars, except TYC 7443-1102-1 and J19560294-3207186, two likely BPMG members identified by Lépine & Simon (2009), are new discoveries. These results demonstrate the potential of the RAVE survey in improving the census of young moving groups. Using the same methods the searches can be extended for other moving groups as well. Moreover, the final version of the RAVE catalogue will contain data for approximately three times more stars, offering a great opportunity for further steps towards a full census of young kinematic groups in the Galactic neighbourhood.
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