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On the local birth place of Geminga

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Abstract. Using estimates of the distance and proper motion of Geminga and the constraints on its radial velocity posed by the shape of its bow shock, we investigate its birth place by tracing its space motion backwards in time. Our results exclude the λ Ori association as the origin site because of the large distance between both objects at any time. Our simulations place the birth region at approximately 90–240 pc from the Sun, between 197° and 199° in Galactic longitude and −16° and −8° in latitude, most probably inside the Cas-Tau OB association or the Ori OB1a association. We discard the possibility of the progenitor being a massive field star. The association of Geminga with either stellar association implies an upper limit of $M \approx 15\ M_\odot$ for the mass of its progenitor. We also propose new members for the Cas-Tau and Ori OB1 associations.

Key words. stars: neutron – pulsars: general – pulsars: individual: Geminga – solar neighbourhood

1. Introduction

The birth place of Geminga has been searched for since its optical counterpart was identified and the first proper motion (Bignami et al. 1993), spin-down age (Bignami & Caraveo 1992) and distance estimates (Halpern & Ruderman 1993) were obtained. Gehrels & Chen (1993) proposed that the Geminga supernova event produced the Local Bubble, while Frisch (1993) argued that Geminga was born somewhere in Orion. Smith et al. (1994) suggested the λ Ori association (also known as Collinder 69) as the most likely birth place, 450 pc away from the Sun. Moreover, the presence of an H I and dust ring surrounding λ Ori, the size and expansion velocity of which are consistent with the spin-down age of the pulsar (Cunha & Smith 1996), reinforced the association between Geminga and this stellar group.

In recent years, the distance and proper motion of Geminga (157^{+59}_{-34} pc and 170 ± 4 mas yr^{-1} respectively) were accurately measured using HST images (Caraveo et al. 1996). As these authors pointed out, Geminga's radial velocity should be about −700 km s^{-1} in order to have reached its current position from the λ Ori association. This is a rather high value compared to its transverse velocity of 126 km s^{-1}. Using the *XMM-Newton* Observatory, Caraveo et al. (2003) succeeded in imaging the bow shock produced by Geminga due to its motion through the ambient interstellar medium. Modeling the bow shock shape yields an inclination of the 3D-velocity to the plane of the sky that is smaller than 30°. Given the transverse velocity inferred from its proper motion and distance, this inclination constrains the radial velocity to lower than 72 km s^{-1} in modulus, therefore an order of magnitude lower than that needed to have reached the current position from λ Ori. This fact prompted us to revisit the potential birth place of Geminga.

2. The λ Ori association

In order to analyze the possibility of Collinder 69 being the birth place of Geminga, we traced the space motion of both objects back in time taking the spin-down age of the pulsar (0.342 Myr) as representative of its true age. We neglected their acceleration in the Galactic potential, since the pulsar age is much shorter than both of their orbital and epicyclic periods. We also neglected possible changes in velocity produced by close encounters with other stars, because the stellar density in the solar neighbourhood and the velocity of Geminga imply a mean time between encounters more than ten orders of magnitude greater than the pulsar age. We computed the position of both Geminga and Collinder 69 for the last 0.342 Myr at intervals of 0.01 Myr, together with a full covariance matrix for them. The distance d between these objects at each timestep and its uncertainty ϵ were also computed. The uncertainty was derived from the covariance matrices of the positions, and takes into account the errors on all measured parameters (Geminga distance and proper motion and Collinder 69 distance, proper motion and radial velocity).

For Collinder 69 we took the coordinates ($\alpha = 5^{\rm h}35^{\rm m}06\overset{\rm s}{.}0$, $\delta = +9°56'00''$), proper motion ($\mu_\alpha \cos\delta = 0.45 \pm 2.80$ mas yr^{-1}, $\mu_\delta = -2.40 \pm 2.80$ mas yr^{-1}) and radial velocity (30.5 ± 2.6 km s^{-1}) from the open cluster catalogue of

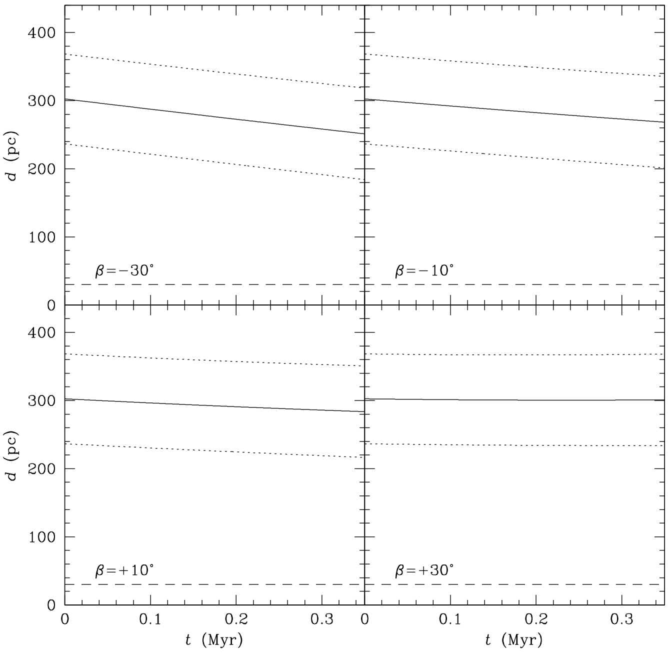

Fig. 1. Distance between Geminga and Collinder 69 as a function of look-back time for four values of the inclination β of the pulsar velocity onto the plane of the sky. Solid lines give the mean distances, while dotted lines indicate the error limits. These errors account for all the uncertainties in both Geminga and Collinder 69 measured parameters. Dashed lines indicate the radius of Collinder 69. This figure shows that the distance between these objects remained much greater than the radius of the cluster for the last 0.342 Myr.

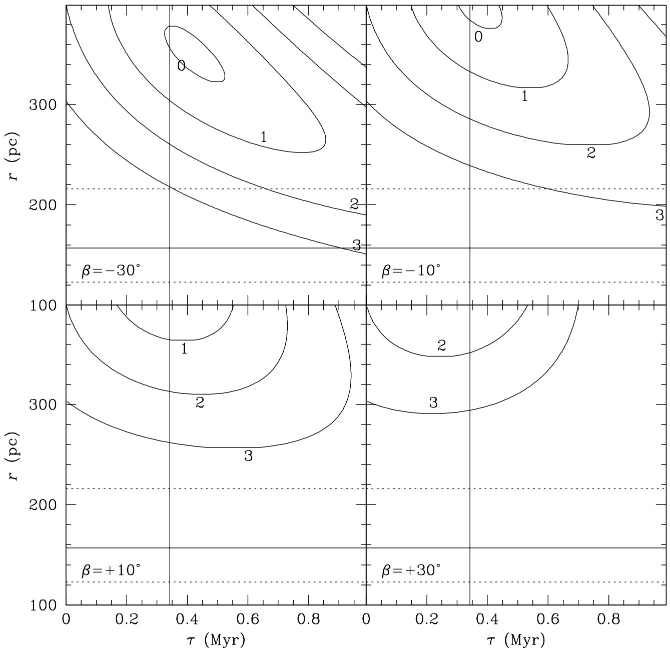

Fig. 2. Contours of the ratio f of the separation $d_{\rm birth}$ of Geminga and the Collinder 69 outer boundary at pulsar birth to its uncertainty $\epsilon_{\rm birth}$. The contours are labeled by the value of f. The vertical and horizontal solid lines respectively indicate the spin-down age and the mean current distance of the pulsar given by parallax measurements. Dotted lines indicate the current distance error. The region inside the $f = 1$ contour, for which the association is possible, is at variance with the current data.

Dias et al. (2002). Its current distance (450 ± 50 pc) was taken from Dolan & Mathieu (2001). For Geminga, we used the coordinates ($\alpha = 6^{\rm h}33^{\rm m}54\overset{\rm s}{.}15$, $\delta = +17°46'12\overset{''}{.}9$) from Caraveo et al. (1998), the parallax (6.36 ± 1.74 mas) and proper motion ($\mu_\alpha \cos\delta = 138 \pm 4$ mas yr^{-1}, $\mu_\delta = 97 \pm 4$ mas yr^{-1}) measured by Caraveo et al. (1996), and a set of four values of the angle β between its velocity and the plane of the sky ($\beta = -30°, -10°, +10°$ and $+30°$) which satisfy the constraints on the bow shock.

Figure 1 presents the distance d between Geminga and Collinder 69 as a function of look-back time t for four values of β. This figure clearly shows that during the whole time interval, the radius of Collinder 69 ($R = 30$ pc, Dolan & Mathieu 2001) is much smaller than the distance between Geminga and this cluster. Hence, it is very unlikely that this stellar association is the birth place of Geminga.

To investigate the effects of possible wrong distance/age estimates, we evolved Geminga backwards in time from different current distances r and computed the separation at birth $d_{\rm birth}$ between the pulsar and the cluster outer boundary nearest to it, and its uncertainty $\epsilon_{\rm birth}$, both as a function of r and age τ. In this case, r is considered a parameter with no error, hence $\epsilon_{\rm birth}$ does not take into account the current distance error. Contours of the function $f = d_{\rm birth}/\epsilon_{\rm birth}$ are displayed in Fig. 2 for four values of β. It shows that a pulsar born within the cluster ($f \leq 1$) would be much more distant than allowed by the parallax measurements and bow shock shape for any age. Hence, the relationship between Geminga and the λ Ori association is very unlikely, unless the cluster distance and/or the pulsar distance/age are seriously revised. Specifically, a pulsar current distance of almost twice the parallax distance and/or an age of twice the spin-down age would be needed to make the association possible for $\beta = -30°$. However, these values are unlikely because other pieces of evidence, such as the agreement between X-ray or optical/UV data and theoretical models (Halpern & Ruderman 1993; Bignami et al. 1996), also favour the spin-down age and parallax distance.

3. Nearby associations

We searched for other suitable birth places for Geminga near the position it had 0.342 Myr ago. This position was very close, less than 200 pc from the Sun for $|\beta| \leq 30°$, so a potential stellar cluster would have a large angular scale making it difficult to determine its structure. The method applied formerly to Collinder 69 is not well suited for these associations, as their centers and boundaries are rather uncertain. Hence, we studied the stellar associations in the solar neighbourhood whose stars are grouped in position and velocity (De Zeeuw et al. 1999) and we directly compared the stellar positions with the likely birth place of Geminga, defined as the error box of its position 0.342 Myr ago. Given $|\beta| \leq 30°$ and the current distance and proper motion uncertainties, the likely birth place is contained in a box defined by $197° < l < 199°$, $-16° < b < -8°$ and 90 pc $< r <$ 240 pc, where (l, b) are the usual Galactic coordinates and r is the distance from the Sun.

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We selected for our analysis all the O and B stars in a slightly greater box, defined by $190° < l < 205°$, $-45° < b < 0°$ and $r < 400$ pc. The coordinates, parallaxes and proper motions of the stars in this box were taken from the All-Sky Compiled Catalogue of 2.5 million stars (ASCC2.5) of Kharchenko (2001). This catalogue has a limiting V magnitude of 12−14, much greater than the apparent magnitude of the faintest B stars if located at 400 pc from the Sun ($V \approx 8$). Hence, we expect no photometric selection effects in our sample. As we need stars with accurate positions to trace the stellar associations, we included in our sample only three groups of stars: 1) stars with accurate Hipparcos parallaxes ($\delta\pi/\pi < 0.25$); 2) stars with accurate distance moduli derived from Walraven photometry by Brown et al. (1994); and 3) stars for which good photometric distances can be computed from the data in the ASCC2.5 catalogue (i.e. from MK spectral types, luminosity classes and Johnson V magnitudes and $B-V$ colours). To compute the stellar distances in the third group, we used the MK calibration of Schmidt-Kaler (1982). Stars that do not comply with any of these conditions were rejected. The selected region contains 181 useful O and B stars, that consist of 83 stars with accurate trigonometric parallaxes, 122 with distance moduli from Brown et al. (1994) and 38 with photometric distances computed from ASCC2.5 data.

The stellar distances computed from ASCC2.5 data take into account the interstellar extinction derived from the comparison between observed and intrinsic stellar colours. A correct determination of the extinction being crucial for a good distance estimate, we compared the observed stellar reddening $E(B-V)_o$ with that derived at the same position in the sky from a Galactic dust reddening map, $E(B-V)_d$ (Schlegel et al. 1998). Away from the Galactic plane, as is the case near Orion, both values should reasonably agree and the dust reddening should give an upper limit to the observed one. Hence, when $E(B-V)_o > E(B-V)_d$ we replaced the former with the latter. In the opposite case we used $E(B-V)_o$ even for stars that show a large difference between both reddening values, as these are probably very nearby stars. Note that replacing the observed colour excess with the dust-derived one in these stars would make their computed distances even smaller, thus making more improbable the higher value of extinction obtained from dust maps.

Using either parallax or photometric distances, we computed the Galactic (X, Y, Z) Cartesian coordinates of the sample stars. Only two of the nearby OB associations listed by De Zeeuw et al. (1999) were found to have stars within the box of interest for Geminga; these are the Cas-Tau and the Ori OB1 associations. A subset of our sample of stars has not only good distances but also good radial velocity determinations. In these cases, taking the radial velocities from the Catalogue of Radial Velocities with Astrometric Data (Kharchenko et al. 2004), we computed the stellar velocities (U, V, W). The velocities were corrected for the solar motion using the values $U_\odot = 9.7$ km s^{-1}, $V_\odot = 5.2$ km s^{-1} and $W_\odot = 6.7$ km s^{-1} (Bienaymé 1998), and for Galactic rotation using the Oort constants $A = 14.8$ km s^{-1} kpc^{-1} and $B = -12.4$ km s^{-1} kpc^{-1}. These velocities were used to identify previously unknown members of the OB associations.

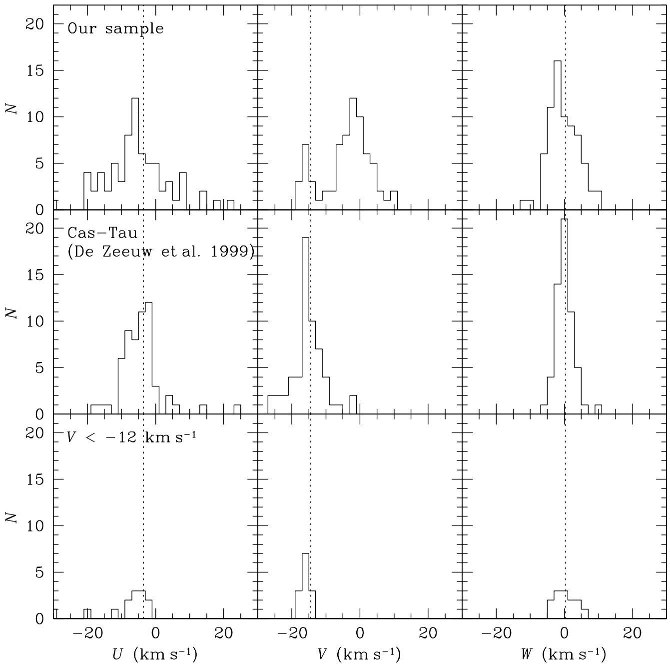

Fig. 3. (U, V, W) velocity distributions for all stars in our sample (upper row), for the Cas-Tau stars identified by De Zeeuw et al. (1999) in and out of our box (middle row), and for the stars from the most negative V peak in our sample ($V < -12$ km s^{-1}, lower row). These last 13 stars include 4 known Cas-Tau members, 8 stars which we propose as new Cas-Tau members on the basis of their position and velocity, and 1 background field object. Dotted lines show the mean (U, V, W) of the Cas-Tau association. All velocities are relative to the LSR.

3.1. The Cas-Tau association

The Cas-Tau association is a very nearby association covering an area of approximately $100° \times 60°$ in the sky, and extending between 125 pc and 300 pc from the Sun. Only 9 of the 83 O and B stars with membership probabilities greater than 50% listed by De Zeeuw et al. (1999) are found in our box. Since the ASCC2.5 contains more stars than the Hipparcos catalogue used by De Zeeuw et al. (1999), we searched for possible new Cas-Tau members inside our box. For this purpose, we compared the velocity distributions in our sample with those of all Cas-Tau members listed by De Zeeuw et al. (1999) with available radial velocities. The mean heliocentric Cas-Tau velocity components are $U_{CT} = -13.24$ km s^{-1}, $V_{CT} = -19.69$ km s^{-1} and $W_{CT} = -6.38$ km s^{-1} (De Zeeuw et al. 1999). Using the solar motion relative to the LSR given by Bienaymé (1998), the Cas-Tau velocity relative to the LSR is $U_{CT,LSR} = -3.54$ km s^{-1}, $V_{CT,LSR} = -14.49$ km s^{-1} and $W_{CT,LSR} = +0.32$ km s^{-1}.

As Fig. 3 shows, the U and W distributions of Cas-Tau stars are quite similar to those in our sample. A difference arises in the V distribution, which is single-peaked for Cas-Tau stars but presents two peaks in our sample. The peak around -2 km s^{-1} is not present for Cas-Tau stars, hence it contains stars not belonging to this association. The most negative peak corresponds to the Cas-Tau distribution and the 13 stars in this peak can be selected by the condition $V < -12$ km s^{-1}. Four of them are indeed known Cas-Tau members from

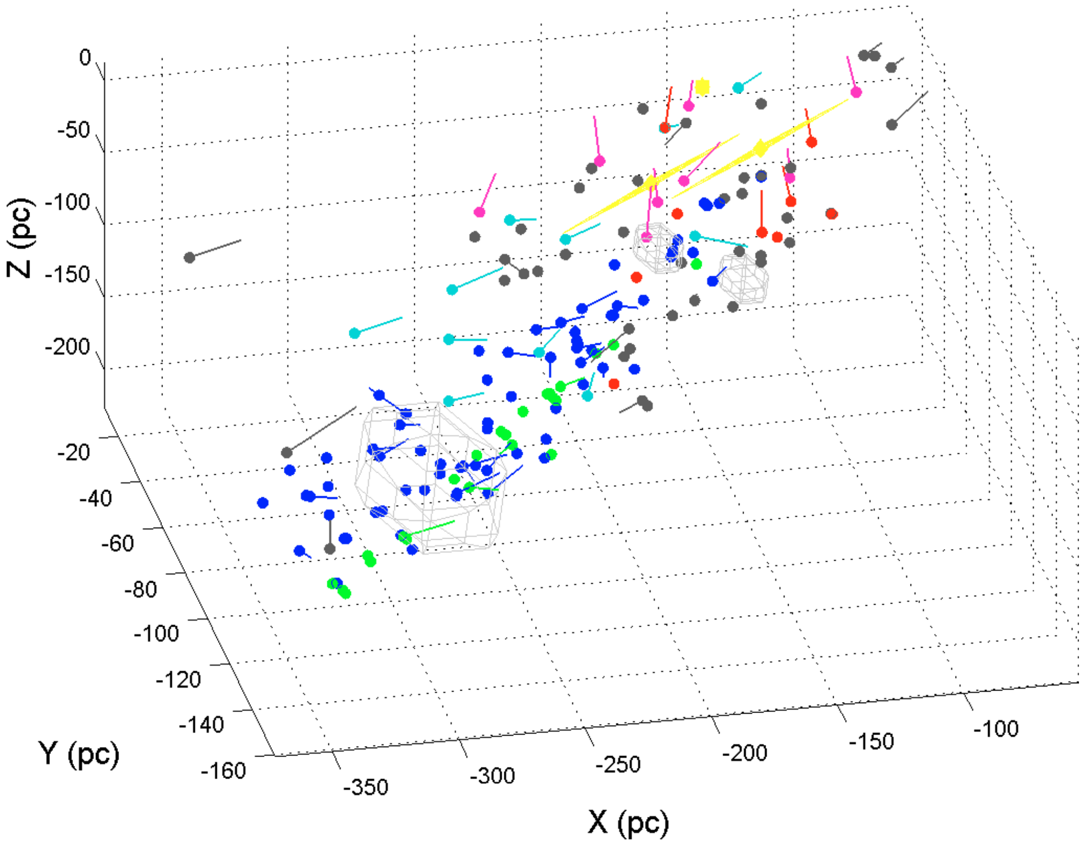

Fig. 4. Spatial distribution of the stars (filled circles) belonging to the Cas-Tau (red), Ori OB1a (dark-blue) and Ori OB1b/c (green) associations. Pink and light-blue circles outline the proposed new members of the Cas-Tau and Ori OB1a associations, respectively, while gray ones represent field stars and stars for which the lack of data prevents any classification. The current position of Geminga is marked by the yellow star, while yellow diamonds surrounded by ellipses indicate the positions at birth and likely birthplaces for $\beta = -30°$ (*left one*) and $\beta = +30°$ (*right one*). The sticks give the stellar velocities when available, their lengths corresponding to the distance traveled in the last 1 Myr. The skeletal spheres, that appear elongated due to projection effects, mark the main location of Ori OB1a (the large one near the lower left corner) and the two more nearby subgroups identified by Platais et al. (1998) as part of Ori OB1a (the small ones near the upper right corner). For all possible values of $|\beta| \leq 30°$, the birth place of Geminga falls among Cas-Tau stars and near the edge of Ori OB1a, or inside it if it is extended to the proposed new members.

De Zeeuw et al. (1999), while one is too far away to belong to this group. The velocity distribution of the others, as well as their 3D-position displayed in Fig. 4, strongly suggest their belonging to the association. So, we propose these 8 stars as new Cas-Tau members[1].

Figure 4 shows the position of the stars in our box according to their membership, together with the confidence regions for the position of Geminga at birth (i.e. 0.342 Myr ago) obtained from the simulations. This figure clearly shows that, for all values of β consistent with the bow-shock data, the birth place of Geminga is located well inside the Cas-Tau association. Hence, Cas-Tau is a very likely candidate for the parent association.

3.2. The Ori OB1 association

The other association contained in our box is the Ori OB1 association, composed of four subgroups named Ori OB1a to Ori OB1d (De Zeeuw et al. 1999). Our box contains 86 of the 132 O and B members of Ori OB1a, 25 of the 84 members of Ori OB1b, only 1 out of 126 in Ori OB1c, and none of the Ori OB1d massive stars (see Fig. 4). The Ori OB1b/c stars in our box are located near the high-longitude edge, far away from the possible birth places. Hence, the only subgroup possibly associated with Geminga is Ori OB1a.

The majority of Ori OB1a stars in Fig. 4 cluster in two subgroups, located at approximately 240 pc and 340 pc from the Sun. The first one is close to the position of two new stellar groups found by Platais et al. (1998) in the Hipparcos data, which they propose to be part of Ori OB1a. The second one corresponds to the main position of Ori OB1a given by De Zeeuw et al. (1999), and is also found in the list of Platais et al. (1998). Hence, Ori OB1a appears as a highly elongated system, with a 5° radius in the plane of the sky and extending from 200 pc to more than 400 pc from the Sun. Although such apparent radial extension could stem from distance uncertainties, in particular in the correction of interstellar extinction, this elongated geometry seems to be real. Using the different distance estimates for the stars which have more than one, we always reach the same conclusion, namely that Ori OB1a extends at least between 200 pc and 400 pc from the Sun.

[1] Their ASCC2.5 catalogue numbers are 845 656, 925 805, 929 279, 1 013 063, 1 013 660, 1 016 668, 1 017 786 and 1 192 880.

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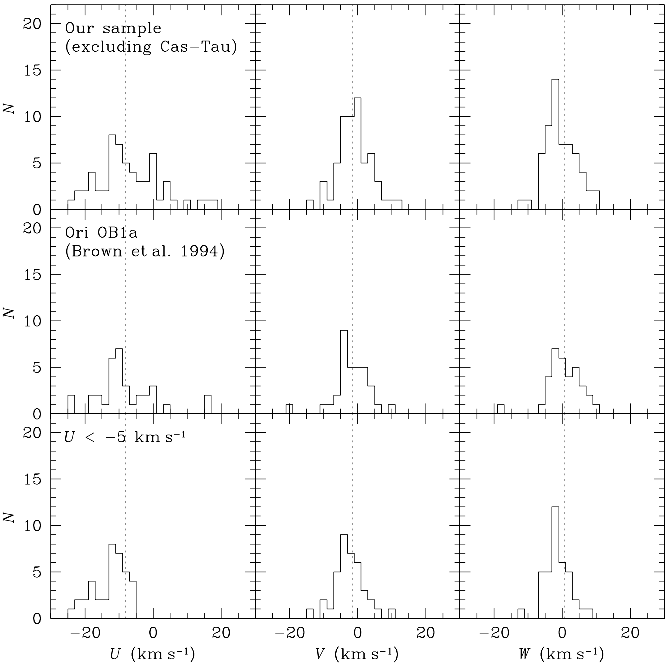

Fig. 5. (U, V, W) velocity distributions for all stars in our sample but in the Cas-Tau association (*upper row*), for the known Ori OB1a stars in and out of our sample (*middle row*), and for the stars with $U < -5$ km s^{-1} in our sample (*lower row*). These 38 stars include 19 known Ori OB1a members, 3 Ori OB1b members and 16 stars sharing the same motion as the Ori OB1a ones, 11 of which are located along the elongated stream, the others being either far from it or much closer to the Sun. Dotted lines show the mean (U, V, W) of the Ori OB1a association. All velocities are relative to the local LSR of each star.

Figure 4 displays the velocity vectors for those stars having radial velocity measurements. Their lengths correspond to the distance traveled in the last 1 Myr. Figure 5 shows that the whole Ori OB1a association moves almost radially away from the Sun, with nearly null V and W components, but an appreciable negative U component with a peak near $U \approx -10$ km s^{-1}. On the other hand, field stars rotating with the Galaxy should not deviate appreciably from a circular orbit and should have a close to null velocity relative to their own LSR. The U distribution of the stars in our box extends to large negative values because of the presence of Ori OB1a members. The smaller sample with $U < -5$ km s^{-1} displayed in the lowest row of Fig. 5 exhibits velocities in good agreement with those of Ori OB1a. They include 19 known Ori OB1a members and 11 possible new ones[2]. In Fig. 4 they appear to be scattered within both subgroups, near the lower longitude edge of the dataset. Five of them indicate a possible extension of the association on the near side, to 140 pc from the Sun. Given the long radial extension of the association and the almost radial velocities of its members, Ori OB1a appears as an unusual vast stream of stars. How it could have been triggered by the expanding wave of the Gould Belt is unclear (Perrot & Grenier 2003).

[2] The ASCC2.5 catalogue numbers of the proposed new members are 846 100, 924 356, 924 551, 1 010 325, 1 012 501, 1 013 386, 1 013 408, 1 103 267, 1 104 520, 1 105 105 and 1 194 478.

Regarding the origin of Geminga, Fig. 4 shows that the near end of the Ori OB1a association (without considering the possible new members) is close to but does not overlap the birth place of the pulsar, hence making the probability of the progenitor of Geminga belonging to Ori OB1a rather low. However, if the possible new members are included, the association extends well over the birth region of Geminga. In this case, Geminga would have been born in a region where the two large Cas-Tau and Ori OB1a associations intersect, making it impossible to decide, by kinematical means, which is the parent one.

3.3. Nearby field stars

It is also possible that the Geminga progenitor is a field star. Nine stars in our sample do not belong to any association and another 27 have neither a previous classification nor radial velocity data, thus making it impossible to know if they belong to an association or not. The earliest main-sequence stars in both groups have spectral type B8V. Their mean mass of approximately 4 $M_\odot$ is far lower than the minimum mass threshold for supernova explosion (7−8 $M_\odot$), and they have lifetimes longer than 150 Myr on the main sequence. Hence, if our small sample is representative of the field population around the birth place of Geminga, this population is much older than that of the local OB associations, and has no stars massive and young enough to account for the production of a pulsar in the last 0.342 Myr.

3.4. The mass of the progenitor of Geminga

If Cas-Tau is the parent association of Geminga, a constraint can be derived on the mass of its progenitor. This association has an age $\tau_{\rm CT} \approx 50$ Myr (De Zeeuw et al. 1999). At this age, stars evolving out of the main sequence now (and also at the birth time of Geminga, since $\tau_{\rm CT} \gg 0.342$ Myr) have a mass of the order of 7 $M_\odot$, marginally consistent with the current theoretical limits for type-II supernovae (hereafter SNII) progenitors of 7−8 $M_\odot$. A study of the individual Cas-Tau stars present in our box shows, on the other hand, that the earliest main-sequence stars are a B3V and possibly a B2IV-V star. Following the calibration of Drilling & Landolt (1999), these stars should have 8−10 $M_\odot$, a mass range consistent with the theoretical limits for SNII progenitors. A similar mass range is obtained from the mean masses of B2V and B3V stars in the catalogue of Belikov (1995). According to these data, the Cas-Tau age would be in the range 25−37 Myr, somewhat younger than the estimate of De Zeeuw et al. (1999). Hence, if born in the Cas-Tau association, the Geminga progenitor would have been among the least massive stars capable of producing a SNII (7−10 $M_\odot$).

On the other hand, the Ori OB1a association has a young age $\tau_{\rm Ori\ OB1a} = 11.4 \pm 1.9$ Myr (Brown et al. 1994), which implies a mass of approximately 15 $M_\odot$ for the stars leaving the main sequence now (and 0.342 Myr ago). This conclusion is supported by the fact that the earliest Ori OB1a main-sequence stars in our sample are of spectral type B1V, which have mean masses of 12−15 $M_\odot$ (Drilling & Landolt 1999; Belikov 1995), large enough to produce type II supernovae.

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Given the uncertainty in the parent association between Cas-Tau and Ori OB1a and the fact that there are no main sequence stars with $M > 15\ M_\odot$ in the potential birth region of the pulsar, we can derive a robust upper limit of 15 $M_\odot$ for the progenitor mass.

4. Conclusions

Using the most recent values and constraints for positions, distances, proper motions and radial velocities of Geminga and the λ Ori association (Collinder 69), we simulated their space motions for the last 0.342 Myr (the spin-down age of the pulsar) and discarded the hypothesis that Geminga was born in this association.

Our simulations locate the most likely birth place of the pulsar between approximately $d = 90{-}240$ pc from the Sun, 197° to 199° in Galactic longitude, and −16° to −8° in Galactic latitude. A search for the possible parent groups of Geminga within this region led us to local OB associations. Among these, the Cas-Tau one, a ≈50 Myr-old group, emerges as the most likely parent association. The birth place of Geminga also lies very near the edge of the Ori OB1a association, a much younger group (11.4 ± 1.9 Myr). If the proposed elongated geometry for this association is confirmed, namely that it constitutes a stream of stars moving almost radially away at distances between 140 and 400 pc from the Sun, then the birth place of Geminga would also be inside Ori OB1a. It would be in the intersection region between Ori OB1a and Cas-Tau. The possibility of the progenitor of Geminga being a field star is unlikely because of their older age in this region. Further constraints on the Geminga birth place could come from X-ray observations with *Chandra*, which could better constrain the inclination of the 3D-velocity onto the plane of the sky. However, because of the large dimensions of Cas-Tau and Ori OB1a, the better localization of the birth place would not alter our conclusions about the parent association.

The origin of the Local Bubble in the Geminga SN explosion (Gehrels & Chen 1993) is not confirmed by our results. The closest birth place for Geminga is found near the Bubble edge and the other possible sites extend much beyond the Bubble wall (Lallement et al. 2003). Recent investigations also show that the Local Bubble could not have been formed by a single SN event, but by multiple SNe which would have taken place in the Pleiades B1 moving group (Berghöfer & Breitschwerdt 2002).

We find similar constraints on the Geminga progenitor mass in both parent associations. It is no greater than 7−10 $M_\odot$ in Cas-Tau, placing it among the least massive stars capable of producing a pulsar. The mass limit is slightly higher, 12−15 $M_\odot$, in the younger Ori OB1a. $M = 15\ M_\odot$ is a robust upper limit for the progenitor mass in this region.

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References

Belikov, A. N. 1995, Bull. Inf. Centre Données Stellaires, 47, 9
Berghöfer, T. W., & Breitschwerdt, D. 2002, A&A, 390, 299
Bienaymé, O. 1998, A&A, 341, 86
Bignami, G. F., & Caraveo, P. A. 1992, Nature, 357, 287
Bignami, G. F., Caraveo, P. A., & Mereghetti, S. 1993, Nature, 361, 704
Bignami, G. F., Caraveo, P. A., Mignani, R., Edelstein, J., & Bowyer, S. 1996, ApJ, 456, L111
Brown, A. G. A., De Geus, E. J., & de Zeeuw, P. T. 1994, A&A, 289, 101
Caraveo, P. A., Bignami, G. F., Mignani, R., & Taff, L. G. 1996, ApJ, 461, L94
Caraveo, P. A., Lattanzi, M. G., Massone, G., et al. 1998, A&A, 329, L1
Caraveo, P. A., Bignami, G. F., DeLuca, A., et al. 2003, Science, 301, 1345
Cunha, K., & Smith, V. V. 1996, A&A, 309, 892
De Zeeuw, P. T., Hoogerwerf, R., & De Bruijne, J. H. J. 1999, AJ, 117, 354
Dias, W. S., Alessi, B. S., Moitinho, A., & Lepine, J. R. D. 2002, A&A, 389, 871
Dolan, C. J., & Mathieu, R. D. 2001, AJ, 121, 2124
Drilling, J. S., & Landolt, A. U. 1999, in Allen's Astrophysical Quantities, ed. A. N. Cox (Springer), 381
Frisch, P. C. 1993, Nature, 364, 396
Gehrels, N., & Chen, W. 1993, Nature, 361, 706
Halpern, J. P., & Ruderman, M. 1993, ApJ, 415, 286
Kharchenko, N. V. 2001, Kinematika Fiz. Nebesn. Tel., 17, 409 (CDS Catalogue I/280)
Kharchenko, N. V., Piskunov, A. E., Scholz, R.-D. 2004, Astron. Nachr., 325, 439 (CDS Catalogue III/239)
Lallement, R., Welsh, B. Y., Vergely, J. L., Crifo, F., & Sfeir, D. 2003, A&A, 411, 447
Perrot, C. A., & Grenier, I. A. 2003, A&A, 404, 519
Platais, I., Kozhurina-Platais, V., & Van Leeuwen, F. 1998, AJ, 116, 2423
Schlegel, D. J., Finkbeiner, D. P., & Davis, M. 1998, ApJ, 500, 525
Schmidt-Kaler, Th. 1982, in Landolt-Börnstein New Series, Group VI, Vol. 2b, ed. K. Schaifers, & H. H. Voigt (Springer-Verlag), 1
Smith, V. V., Cunha, K., & Plez, B. 1994, A&A, 406, 111