Open Clusters ASCC21 as a Probable Birthplace of the Neutron Star Geminga

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Abstract—We analyze the encounters of the neutron star (pulsar) Geminga with open star clusters in the OB association OriOB1a through the integration of epicyclic orbits into the past by taking into account the errors in the data. The open cluster ASCC21 is shown to be the most probable birthplace of either a single progenitor star for the Geminga pulsar or a binary progenitor system that subsequently broke up. Monte Carlo simulations of Geminga–ASCC21 encounters with the pulsar radial velocity $V_r = -100 \pm 50$ km s$^{-1}$ have shown that close encounters could occur between them within $\leq 10$ pc at about $t = -0.52$ Myr. In addition, the trajectory of the neutron star Geminga passes at a distance of $\approx 25$ pc from the center of the compact OB association $\lambda$ Ori at about $t = -0.39$ Myr, which is close to the age of the pulsar estimated from its timing.

INTRODUCTION

Young massive O and B stars can run away from the stellar group (an open cluster or an OB association) where they were born. Such stars are called runaways; they are identified by high (> 30 km s$^{-1}$) space velocities. Two main runaway scenarios are known (see the review by Hoogerwerf et al. 2001). The first scenario is related to the evolution of a binary system and the explosion of one of the components as a supernova. In this case, one of the components can receive a high kick velocity due to an asymmetric explosion and a significant mass loss by the binary. A massive runaway star and its former companion, a neutron star or a black hole, are the breakup products of such a binary. The second scenario is related to the dynamical evolution of an initial stellar group. Mutual encounters of close binary and multiple systems are the most efficient ejection mechanism.

The best-known runaway stars, such as $\zeta$ Oph, $\xi$ Per, $\mu$ Col, AE Aur, $\zeta$ Pup, and others, were discovered by Blaauw (1961; 1993). Probable parent associations were determined for some of them. Hoogerwerf et al. (2001) considered the problem of determining the most probable birthplaces of pulsars using data from the Hipparcos (1997) Catalogue. Based on a more complete list of runaway OB stars, Schilbach and Röser (2008) showed that the parent open cluster or OB association to which they belonged could be pinpointed with a high probability for most ($\approx 90\%$) of the O stars in the solar neighborhood (within $< 1$ kpc), including those that were previously believed to be field stars.

The problem of determining probable birthplaces of nearby young neutron stars associated with the Gould Belt (Popov et al. 2003; Motch et al. 2006) is of great interest. One of these stars is Geminga (PSR J0633+1746), to which this paper is devoted.
In contrast to the overwhelming majority of pulsars, Geminga was discovered in 1973 as a gamma-ray source from the SAS-2 satellite. The impulsive behavior of its signals was first detected in the X-ray (Halpern and Holt 1992) and gamma-ray (Burch et al. 1992; Bignami and Caraveo 1992) bands and, only several years later, in the radio band (Kuzmin and Losovsky 1997; Malofeev and Malov 1997). The age of the Geminga pulsar, 0.342 Myr, was first determined from its timing (P/2P, where P and 2P are the pulsar period and its first derivative, respectively) by Bignami and Caraveo (1992). Bignami et al. (1993) identified this pulsar in the optical band with a 25.5-magnitude object and were the first to determine the components of its proper motion. The distance to the Geminga pulsar, \( r = 150 - 400 \) pc, was first estimated by Halpern and Ruderman (1993).

The present-day quality of the spectra for pulsars is too low for their radial velocities to be determined. At the same time, an arc-like feature produced by the interaction of pulsar emission with the interstellar medium is observed near the neutron star Geminga (Caraveo et al. 2003; Shibanov et al. 2006). Modeling the shape of this arc-like feature (Caraveo et al. 2003) yielded a constraint on the magnitude of the radial velocity for the Geminga pulsar (|\( V_r \)| \( \leq 100 \) km s\(^{-1} \)). Given this constraint, the radial velocity is a free parameter in our studies.

One of the first hypotheses that the birthplace of the Geminga pulsar is associated with the Local Bubble was proposed by Gehrels and Chen (1993). According to this hypothesis, a positive radial velocity of the pulsar should be adopted. In the opinion of Frisch (1993), this pulsar originated in the Orion OB association, suggesting that its radial velocity is negative. The modeling by Smith et al. (1994) showed that the compact OB association \( \lambda \) Ori (Cr 69) at \( V_r \approx -100 \) km s\(^{-1} \) could be a suitable birthplace of the pulsar.

Using Hubble Space Telescope (HST) observations, Caraveo et al. (1996) were the first to determine the trigonometric parallax of the pulsar, \( \pi_{tr} = 6.36 \pm 1.74 \) mas, which corresponds to its distance \( r = 157^{+59}_{-34} \) pc. They also determined the proper motion components, \( \mu_\alpha \cos \delta = 138 \pm 4 \) mas yr\(^{-1} \) and \( \mu_\delta = 97 \pm 4 \) mas yr\(^{-1} \). The search for a probable birthplace of the neutron star Geminga carried out by Pellizza et al. (2005) based on these data led them to conclude that this birthplace could be in a fairly close solar neighborhood (\( r = 90 - 240 \) pc) and is related either to the relatively old (\( \approx 50 \) Myr) CasTau association or to the edge of the younger (\( \approx 11 \) Myr) OB association Ori OB1a.

The currently available HST observations of Geminga (Faherty et al. 2007) showed that the new parallax, \( \pi_{tr} = 4.0 \pm 1.3 \) mas (\( r = 250^{+120}_{-62} \) pc), differs significantly from the previously published one (Caraveo et al. 1996), which should inevitably affect the results of searching for its birthplace.

The goal of this paper is to determine the most probable birthplace of the Geminga pulsar by simulating its motion in space into the past using the most resent data on open star clusters (Kharchenko et al. 2007) and individual stars (van Leeuwen 2007). The objectives set here are accomplished using the method of statistical Monte Carlo simulations—we determine the epicyclic orbits of objects by taking into account the corridor of errors in the observational data.

**DATA**

The input data on the objects under consideration, such as their equatorial coordinates, proper motion components, radial velocities, and parallaxes, are given in the table. The data
Table 1: Data on stars and open star clusters Object.

| Object | $\alpha_{(J2000.0)}, \delta_{(J2000.0)}$ | $\mu_\alpha \cos \delta, \mu_\delta, \text{mas yr}^{-1}$ | $\pi, \text{mas}$ | $V_r, \text{km s}^{-1}$ | Distance, pc |
|--------|--------------------------------|---------------------------------|----------------|----------------|-------------|
| ASCC16 | $5^\circ 24\arcmin 36\arcsec\ 1^\circ 48\arcmin 00\arcsec$ | $0.75 \pm 0.22\ -0.18 \pm 0.29$ | $20.80 \pm 4.60$ | | 460 (2) |
| ASCC18 | $5^\circ 26\arcmin 09.6\arcsec\ 0^\circ 49\arcmin 12\arcsec$ | $0.89 \pm 0.28\ -0.02 \pm 0.25$ | $24 \pm 10$ | | 500 (2) |
| ASCC20 | $5^\circ 28\arcmin 44.4\arcsec\ 1^\circ 37\arcmin 48\arcsec$ | $-0.09 \pm 0.21\ 0.51 \pm 0.19$ | $22.97 \pm 4.80$ | | 450 (2) |
| ASCC21 | $5^\circ 28\arcmin 58.8\arcsec\ 3^\circ 39\arcmin 00\arcsec$ | $0.52 \pm 0.25\ -0.62 \pm 0.28$ | $19.77 \pm 1.12$ | | 500 (2) |
| $\lambda$ Ori (Cr 69) | $5^\circ 35\arcmin 09.6\arcsec\ 9^\circ 42\arcmin 00\arcsec$ | $0.40 \pm 0.47\ -1.93 \pm 0.34$ | $31.38 \pm 1.42$ | | 438 (2) |
| HIP 22061 | $4^\circ 44\arcmin 42.1\arcsec 1571\ 0^\circ 34\arcmin 05\arcsec .418$ | $-44.02 \pm 0.52\ -30.04 \pm 0.50$ | $2.99 \pm 0.63$ (1) | | 9.0 \pm 4.4 (3) |
| HIP 29678 | $6^\circ 15\arcmin 08\arcsec .4567\ 13^\circ 51\arcmin 03\arcsec .859$ | $25.23 \pm 0.50\ 11.44 \pm 0.30$ | $2.72 \pm 0.43$ (1) | | 35.8 \pm 1.0 (4) |
| Geminga | $6^\circ 33\arcmin 54\arcsec .1530\ 17^\circ 46\arcmin 12\arcsec .909$ | $142.2 \pm 1.2\ 107.4 \pm 1.2$ | $4.0 \pm 1.3$ (5) | | |

Note. (1) van Leeuwen (2008), (2) CRVOCA (Kharchenko et al. 2007), (3) PCRV (Gontcharov 2006), (4) CRVAD-2 (Kharchenko et al. 2007), (5) Faherty et al. (2007).

for all of the stars used were taken from a revised version of the Hipparcos Catalogue (van Leeuwen 2007). For the Geminga pulsar, we use new data from Faherty et al. (2007), which were obtained from 18-month-long HST observations of the star. The CRVOCA Catalog (Kharchenko et al. 2007) served as the source of data for open clusters. The distance estimates in this catalog are based on a photometric method with an error of $\approx 20\%$. We calculated the parallaxes for each open cluster based on the distances given in the last column of the table.

Four groups, Ori OB1a, b, c, and d (Blauu1964), with ages of 11.4 ± 1.9, 1.7 ± 1.1, 4.6 ± 2, and < 1 Myr, respectively, are identified in the Orion association (Brown et al. 1994). According to Kharchenko et al. (2005), the Ori OB1a association includes four open clusters, ASCC16, ASCC18, ASCC20, and ASCC21, with ages of 8.5, 13.2, 22.4, and 12.9 Myr, respectively. The question of whether each of them is an open cluster or an association is still under discussion. In this respect, ASCC16, which is also designated as the group 25 Ori (Briceño et al. 2005; McGehee 2006), is the best-studied open cluster. Here, a fairly dense concentration of young T Tauri stars was detected. Their analysis led McGehee (2006) to conclude that this is a gravitationally unbound group rather than an open cluster.

The OB–T association/cluster $\lambda$Ori is located near the Ori OB1a association. A compact H II region (S264) is associated with the star $\lambda$Ori. In a wider neighborhood of the center with a radius of $\approx 5^\circ$ (40 pc), the association is surrounded by a ring of molecular clouds and gas (Maddalena and Morris 1987). This star-forming region was studied in a series of papers by Dolan and Mathieu (1999, 2001, 2002). Based on Strömgren photometry, they estimated...
the distance to the open cluster λOri, 450 ± 50 pc. Ten B stars forming the cluster proper were shown to concentrate in a sky field with a radius of ≈ 1° (8 pc) around the central star of the cluster λOri (Sp: O8III) with an age of ≈ 5.5 Myr. In a wider neighborhood of the center with a radius of ≈ 5° (40 pc), they detected several concentrations of young T Tauri stars. On the whole, Dolan and Mathieu concluded that: (a) star formation in the cluster λOri ceased ≈ 1 Myr ago after the supernova explosion; (b) the group of young massive stars is currently not gravitationally bound; and (c) star formation currently goes on in the clouds B30 and B35 located on the periphery of the association.

METHODS

Orbit Construction

In this paper, we use a rectangular Galactic coordinate system with the axes directed away from the observer toward the Galactic center (l = 0°, b = 0°, the X axis), along the Galactic rotation (l = 90°, b = 0°, the Y axis), and toward the North Galactic Pole (b = 90°, the Z axis). The corresponding space velocity components of the objects U, V, W are also directed along the X, Y, Z axes (Kulikovskii 1985).

The epicyclic approximation (Lindblad 1927, 1959) allows the orbits of stars to be constructed in a coordinate system rotating around the Galactic center. We assume that the origin of the coordinate system coincides with the local standard of rest and that the stars move along epicycles in the direction opposite to the Galactic rotation. We use the method in the form given by Fuchs et al. (2006):

\[
X(t) = X(0) + \frac{U(0)}{\kappa} \sin(\kappa t) + \frac{V(0)}{2B} (1 - \cos(\kappa t)),
\]

\[
Y(t) = Y(0) + 2A \left( X(0) + \frac{V(0)}{2B} \right) t - \frac{\Omega_0}{B\kappa} V(0) \sin(\kappa t) + \frac{2\Omega_0}{\kappa^2} U(0)(1 - \cos(\kappa t)),
\]

\[
Z(t) = \frac{W(0)}{\nu} \sin(\nu t) + Z(0) \cos(\nu t),
\]

where \( t \) is the time in Myr (pc/Myr=0.978 km s\(^{-1}\)), which is measured into the past; \( A \) and \( B \) are the Oort constants; \( \kappa = \sqrt{-4\Omega_0 B} \) is the epicyclic frequency; \( \Omega_0 \) is the angular velocity of Galactic rotation of the local standard of rest, \( \Omega_0 = A - B \); and \( \nu = \sqrt{4\pi G \rho_0} \) is the frequency of the vertical oscillations, where \( G \) is the gravitational constant and \( \rho_0 \) is the star density in the solar neighborhood. The space velocities of the objects are calculated for any necessary time using the formulas

\[
U(t) = U(0) \cos(\kappa t) + \frac{\kappa}{2B} V(0) \sin(\kappa t),
\]

\[
V(t) = 2A \left( X(0) + \frac{V(0)}{2B} \right) - \frac{\Omega_0}{B} V(0) \cos(\kappa t) + \frac{2\Omega_0}{\kappa} U(0) \sin(\kappa t)),
\]

\[
W(t) = W(0) \cos(\nu t) - Z(0) \nu \sin(\nu t).
\]

The parameters \( X(0), Y(0), Z(0) \) and \( U(0), V(0), W(0) \) in Eqs. (1) and (2) denote, respectively, the current positions and velocities of the objects. The velocities \( U, V, W \) are given relative to the local standard of rest with \((U, V, W)_{\text{LSR}} = (10.00, 5.25, 7.17) \text{ km s}^{-1}\) (Dehnen and Binney 1998). Following Fuchs et al. (2006), we adopted \( \rho_0 = 0.1 M_\odot \text{ pc}^3 \), which gives
\( \nu = 74 \text{ km s}^{-1} \text{ kpc}^{-1} \). We also used the Oort constants \( A = 13.7 \pm 0.6 \text{ km s}^{-1} \text{ kpc}^{-1} \) and 
\( B = -12.9 \pm 0.4 \text{ km s}^{-1} \text{ kpc}^{-1} \) that we found previously (Bobylev 2004) by analyzing the
independent determinations of these parameters by various authors; \( \kappa = 37 \text{ km s}^{-1} \text{ kpc}^{-1} \)
corresponds to these values.

Statistical Simulations
In accordance with the method of statistical Monte Carlo simulations, we compute 3 million
orbits for each object by taking into account the random errors in the input data. For each
pair of orbits belonging to two different objects, we calculate the encounter parameter
\( \Delta r = \sqrt{\Delta X^2(t) + \Delta Y^2(t) + \Delta Z^2(t)} \).

The parameters of the objects are distributed normally with a dispersion \( \sigma \). As was
shown by Hoogerwerf et al. (2001), the random errors in the equatorial coordinates of stars
and open clusters do not affect noticeably the simulation results. As a result, the errors
are added only to the proper-motion components, parallax, and radial velocity of an object.
The parameters are listed in the table.

The distribution of the encounter parameter in a certain neighborhood can be represented
as a histogram (see below). We calculated the expected distribution \( F_{3D} \) of the minimum
separation \( \Delta r \) using a formula from Hoogerwerf et al. (2001),

\[
F_{3D}(\Delta r) = \frac{\Delta r}{2\sigma \mu \sqrt{\pi}} \left\{ \exp \left[ -\frac{(\Delta r - \mu)^2}{4\sigma^2} \right] - \exp \left[ -\frac{(\Delta r + \mu)^2}{4\sigma^2} \right] \right\}
\]

(3)

for appropriate mean \( \mu \) and dispersion \( \sigma \). When \( \mu \) may be considered close to zero, Hooger-
werf et al. (2001) obtained the expression

\[
F_{3D}(\Delta r) = \frac{\Delta r^2}{2\sigma^3 \sqrt{\pi}} \exp \left[ -\frac{\Delta r^2}{4\sigma^2} \right].
\]

(4)

For such open clusters as ASCC21 and \( \lambda \)Ori, the tidal radius is 13.7 ± 1.8 and 7.7 ± 1.4 pc,
respectively (Piskunov et al. 2008). Therefore, in our simulations, we choose the character-
istic radius of the neighborhood in which close encounters of stars with clusters occur to be
10 pc.

Analysis of the orientation of the shock front ahead of the pulsar yields a constraint on
its radial velocity. A fairly symmetric shock was detected near the neutron star Geminga
(Caraveo et al. 2003; Shibanov et al. 2006). Modeling its shape suggests that the radial
velocity of Geminga is relatively low, \(|V_r| \leq 72 \text{ km s}^{-1}\); the angle \( \beta \) between the total space
\( (V) \) velocity vector and the tangential \( (V_\perp) \) velocity is \(|\beta| \leq 30^\circ\) (Caraveo et al. 2003; Pellizza
et al. 2005). For the new data (table), \( \beta = 30^\circ.7 \), where \(|\cos \beta| = V_\perp/V \), corresponds to
the radial velocity \(|V_r| = 100 \text{ km s}^{-1}\). Therefore, for the Geminga pulsar, we take its model
radial velocity \( V_r = -100 \pm 50 \text{ km s}^{-1} \).

RESULTS
Figure 1 shows the positions and trajectories of the open clusters in the Ori OB1a association,
the cluster \( \lambda \)Ori, and the neutron star Geminga for a radial velocity of \(-100 \pm 50 \text{ km s}^{-1}\)
over 1 Myr into the past (with marks at 0.5-Myr intervals). To construct the trajectories
in Galactic coordinates, we first calculated the rectangular coordinates \( X(t), Y(t), \) and \( Z(t) \)
from Eqs. (1) and then found the corresponding spherical Galactic coordinates \( l(t) \) and \( b(t) \) from them. As can be seen from the figure, the trajectory of the Geminga pulsar passes near two open clusters, ASCC21 and \( \lambda \) Ori. The two dotted lines in Fig. 1 indicate the pulsar trajectories calculated with extreme \((\pm 3\sigma)\) values of the proper-motion components.

Our simulations of the Geminga encounter with the cluster ASCC21 yielded the following results. Out of the 3 million orbits obtained by introducing random errors with a given dispersion for both pulsar and cluster, 10 5441 encounters occur at separations \( \Delta r \leq 10 \) pc \((3.5\%)\). In 3137 of the 10 5441 cases \((3.0\%)\), the encounters at about \( t = -0.52 \) Myr occur in the neighborhood of ASCC21 with a radius \( \leq 10 \) pc and with the center lying on the cluster trajectory obtained from the data without introducing any errors. Figure 2a shows the expected distribution \( F_{3D} \) of the minimum separation \( \Delta_r \) calculated from Eq. (3) for the adopted mean \( \mu = 7.75 \) pc and dispersion \( \sigma = 1.0 \) pc. The domain of admissible values of \( V_r, \pi, \mu_\alpha \cos \delta (\mu_\alpha^*) \), and \( \mu_\delta \) at which 3137 encounters occur are shown in Fig. 3 for the Geminga pulsar and Fig. 4 for the cluster ASCC21. The horizontal and vertical lines in Figs. 3 and 4 pass through the nominal values of the parameters used.

Figure 3 shows the set of lines representing the region that satisfies the condition \( |\beta| \leq 30^\circ \) for the \( V_r - \pi \) relation. The lines were obtained in accordance with the relation \( V_r = V \perp \tan \beta \). The solid and dotted lines correspond to the angles \( \beta = \pm 30^\circ \) and \( \beta = \pm 15^\circ \), respectively. As we see from the figure, most of the model points fall into the interval \( |\beta| \leq 30^\circ \), thereby satisfying the constraint on the pulsar radial velocity determined from an analysis of the shock shape (Caraveo et al. 2003; Pellizza et al. 2005).

Our simulations of the encounter of the neutron star Geminga with the cluster \( \lambda \) Ori revealed no mutual encounters at separations \( \leq 10 \) pc. However, there are less close encounters. Thus, for example, out of the 300 000 model orbits, 25 745 encounters occur at separations \( \Delta_r \leq 25 \) pc \((8.5\%)\); in 2686 of the 25 745 cases, the encounters occur within \( \leq 30 \) pc \((10\%)\) of the cluster \( \lambda \) Ori at about \( t = -0.39 \) Myr.

Our simulations of the Geminga encounter with the cluster ASCC16 yielded the following results: out of the 3 million orbits, 27 848 encounters occur at separations \( \Delta_r \leq 10 \) pc \((0.9\%)\); in 1475 of the 27 848 cases, the encounters occur within \( \leq 50 \) pc of the cluster ASCC16 at about \( t = -0.63 \) Myr. Thus, in this case, we have a factor of 4 fewer encounters than in the case of ASCC21.

To determine a possible candidate for the binary component with the neutron star Geminga in the past, we selected known rapidly flying stars whose trajectories passed near the Ori OB1 association on the celestial sphere in a time interval of 2 Myr (Fig. 2 from Hoogerwerf et al. 2001): HIP 22061, HIP 27204, and HIP 29678 (numbers 4, 6, and 7 in the list of Hoogerwerf et al., 2001).

For HIP 22061, there are encounters with the Geminga pulsar at \( t \approx 0.6 \) Myr but within \( \Delta_r \leq 20 \) pc, i.e., the encounters are not close. For HIP 27204, there are no encounters with the Geminga pulsar within \( \Delta_r \leq 20 \) pc. For HIP 29678, there are close encounters with the Geminga pulsar. We found that out of the 3 million orbits, 124 544 encounters occurred at separations \( \Delta_r \leq 10 \) pc \((4\%)\) at \( t = -0.14 \) Myr, which is half the pulsar age calculated from its timing.

According to Hoogerwerf et al. (2001), the stars HIP 22061 (B2.5V) and HIP 29678 (B1V) have masses of \( 8.6M_\odot \) and \( 11.5M_\odot \), respectively. They are probably the components of a dissociated multiple (HIP 29678 is a visual binary) system. We found that out of the 300 000 orbits, 18 165 encounters occur between these two stars at separations \( \Delta_r \leq 10 \) pc \((6\%)\); in addition, 5310 of the 18165 encounters occur within \( \Delta_r \leq 50 \) pc of the cluster
λOri at about $t = -1.12$ Myr. As can be seen from the table, the localization error for each of the objects under consideration is $\approx 20\%$. This served as a basis for choosing the size of the neighborhood (50 pc). Therefore, our results are consistent with the assumption that HIP 22061 and HIP 29678 ran away from the neighborhood of the cluster λOri about 1.1 Myr ago. Figure 5a shows the expected distribution $F_{3D}$ of the minimum separation $\Delta r$, calculated from Eq. (4) for the dispersion $\sigma = 1.2$ pc. This is an example of very close encounters; thus, for example, the separation between the two stars was only $\leq 0.12$ pc in two model cases.

The conclusion that HIP 22061 and HIP 29678 are the remnants of a dissociated binary or multiple system is in agreement with the analysis of the motion of these stars performed by Hoogerwerf et al. (2001) using Hipparcos data. However, Hoogerwerf et al. (2001) questioned the involvement of the star λOri in the event that led to the breakup of the multiple system HIP 22061–HIP 29678. This conclusion was drawn from the fact that the point on the celestial sphere with coordinates $(l, b) = (196^\circ.5, -12^\circ.0)$ was found as a probable current position of the parent cluster for HIP 22061 and HIP 29678, which differs by one degree from the current position of the center of the cluster λOri. The velocity difference effect can be seen in Fig. 1. More specifically, if the cluster λOri were located one degree to the left, then all three trajectories (λOri, HIP 22061, and HIP 29678) would intersect at the same time, $t \approx -1$ Myr.

The kinematic paradox in the motion of the star λOri was pointed out by Maddalena and Morris (1987). It lies in the fact that the position of the star λOri in the past does not coincide with the center of the ring of molecular hydrogen clouds expanding with a velocity of $14.3 \pm 2.5$ km s$^{-1}$. We are talking about a velocity difference of $7-10$ km s$^{-1}$. According to Maddalena and Morris (1987), the coordinates of the ring center are $(\alpha, \delta)_{1950} = (5^h29^m.8 \pm 1^m.6, 9^\circ54^\prime \pm 24^\prime)$ and, hence, $(l, b) = (194^\circ.7 \pm 0^\circ.4, -12^\circ.5 \pm 0^\circ.4)$ (in our view, these coordinates reflect the position of the supernova at the time of its explosion). The position of the ring center remarkably coincides with the point of intersection of the trajectories for HIP 22061 and HIP 29678 that we found, namely, $(l, b) = (194^\circ.6 \pm 0^\circ.2, -12^\circ.2 \pm 0^\circ.2)$. The errors here were estimated from the relation $\varepsilon_{l, b} = \arctan(\sigma/r)$, where $r = 438$ pc, and from the dispersion $\sigma = 1.2$ pc found above (Fig. 5a).

Let us assume that the HIP 22061–HIP 29678 pair is a relic of the system (the cluster λOri) before the time that preceded the dynamical “event” as a result of which the star λOri received an additional kick ($-10$ km s$^{-1}$). In this case, we obtain an independent estimate at the time of the event — it could occur no later than 1.12 Myr ago. Moreover, it follows from the above assumption that the point of intersection of the HIP 22061–HIP 29678 pair indicates the position of the center of the cluster λOri at a time of $-1.12$ Myr. This suggests that the supernova explosion that gave rise to the ring of molecular clouds around the cluster λOri occurred no later than $-1.12$ Myr.

We can see that the pair of runaway stars HIP22061 and HIP 29678 is of great interest in studying the evolution of the cluster λOri. We consider the close encounters of HIP 29678 with the Geminga pulsar found above as a purely geometric effect. If both these objects (HIP 29678 and Geminga) resulted from the evolution of a binary progenitor system, then its trajectory before its breakup could be arbitrary and the encounter of the HIP 22061–HIP 29678 trajectories would not be as shown in Fig. 1.
1 DISCUSSION

Based on an isochronous age estimate for the cluster ASCC21, 12.9 Myr (Kharchenko et al. 2005), we can estimate the minimum mass of a post-main sequence star. For example, based on Fig. 11.5 from Sakhibullin (2003) for log \( t \) = 7.11, we obtain an estimate of the mass for such a star, \( \approx 15M_\odot \). On the other hand, there are no stars bluer than a B1.5V-type star (HIP 25861) in the cluster ASCC21. Therefore, the more massive B0V-type stars, whose masses are known to be \( \approx 15M_\odot \), can be assumed to have already left the main sequence. A more detailed comparison with isochrones, for example, from Schaller et al (1992), also leads to a similar conclusion.

We may conclude that in the case of ASCC21, the mass of the probable progenitor star for the Geminga pulsar satisfies well the condition for the formation of neutron stars with \((10 - 12)M_\odot < M < (30 - 40)M_\odot \) (Zasov and Postnov 2006).

The cluster λOri is considerably younger. Dolan and Mathieu (2002) estimated the mass and age of the most massive cluster star, λOri, to be 26.8\( M_\odot \) and \( \approx 5.5 \) Myr, respectively. Thus, the higher-mass stars have already evolved. Therefore, the cluster ASCC21 appears more preferable in the scenario with a single progenitor star for the Geminga pulsar.

Our simulations showed that there is a probability (\( \approx 3\% \)) of the simple scenario in which the pulsar was formed in ASCC21 at \( t = -0.52 \) Myr and has since moved in the same direction with the initially received velocity.

As was pointed out by Yakovlev et al. (1999), the characteristic (i.e., dynamical, determined from timing) age of Geminga was estimated to within a factor of \( \sim 3 \). Glitches in period, which are also observed in the Geminga pulsar (Jackson et al. 2002), are among the factors that affect the dynamical age estimates for pulsars. On the other hand, the neutron star Geminga exhibits thermal radiation, which allows its age boundaries to be estimated by comparison with neutron star cooling models. Thus, for example, we can see from the data in Table 3 and the cooling curves in Fig. 20 from Yakovlev et al. (1999) that the upper limit for the Geminga age in the blackbody model reaches \( \approx 1 \) Myr. Similar estimates of the age boundaries for the Geminga pulsar, 0.1 – 1 Myr, can be found in Page et al. (2004).

Thus, the scenario for the formation of Geminga in the cluster ASCC21 at \( t = -0.52 \) Myr is consistent with the time intervals considered. For this scenario to be realized, first, the Geminga parallax must fall within the range 2–3 mas (Fig. 3) and, second, there must be traces of the supernova remnant around ASCC21, which is not yet observed. On the other hand, such a remnant could disperse completely in \( \approx 0.5 \) Myr.

The assumption that the progenitor star from which the Geminga pulsar subsequently originated was formed in ASCC21 appears more realistic. This viewpoint is in agreement with the scenario by Smith et al. (1994), who believe the Geminga pulsar to be either the remnant of a runaway OB star ejected from the Orion OB1a association and exploded as a supernova outside this group or the result of a supernova explosion in the cluster λOri. Cunha and Smith (1996) provide arguments that the ring of molecular hydrogen clouds around the cluster λOri has an age of 300–370 thousand years, in good agreement with the dynamical age estimate for the neutron star Geminga.
CONCLUSIONS

Analysis of the possible encounters of the neutron star Geminga with open clusters in the Ori OB1a association in the past led us to conclude that the open cluster ASCC21, a member of the Ori OB1a association, is the most likely candidate for the birthplace of either a binary progenitor system that subsequently broke up or a single progenitor star. Monte Carlo simulations of the encounters of this pair with Geminga's radial velocity $V_r = -100 \pm 50$ km s$^{-1}$ showed that close encounters of the pulsar with this open cluster could occur within $\leq 10$ pc at about $t = -0.52$ Myr. In addition, the trajectory of the Geminga pulsar passes at a distance of about $25$ pc from the center of the compact OB association $\lambda$Ori at about $t = -0.39$ Myr.

Previously, the Geminga pulsar was assumed to be related to a wide neighborhood of the Ori OB1a association, while we found the specific open cluster (ASCC21) from which the massive progenitor star or the progenitor binary could be ejected.

In addition, the kinematics of the pair of runaway stars HIP 22061–HIP 29678 under the assumption that they were members of the cluster $\lambda$Ori in the past allowed us to obtain an independent estimate for the time of the dynamical “event” as a result of which the star $\lambda$Ori received an additional kick—it could occur no later than 1.12 Myr ago.

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REFERENCES

1. G.F. Bignami and P.A. Caraveo, Nature 357, 287 (1992).
2. G.F. Bignami, P. A. Caraveo, and S. Mereghetti, Nature 361, 704 (1993).
3. A. Blaauw, Bull. Astron. Inst. Netherlands 15, 265 (1961).
4. A. Blaauw, Ann. Rev. Astron. Astrophys. 2, 213 (1964).
5. A. Blaauw, ASP Conf. Ser. 35, 207 (1993).
6. V. V. Bobylev, Pisma Astron. Zh. 30, 185 (2004) [Astron. Lett. 30, 159 (2004)].
7. C. Briceño, N. Calvet, J. Hernandez, et al., Astron. J. 129, 907 (2005).
8. A. G. A. Brown, E. J. de Geus, and P. T. de Zeeuw, Astron. Astrophys. 289, 101 (1994).
9. D. L. Burch, K. T. S. Brasier, C. E. Fitchel, et al., Nature 357, 357 (1992).
10. P. A. Caraveo, G. F. Bignami, R. Mignani, et al., Astroph. J. 604, 339 (1996).
11. P. A. Caraveo, G. F. Bignami, De Luca, et al., Science 301, 134 (2003).
12. K. Cunha and V. V. Smith, Astron. Astrophys. 309, 892 (1996).
13. W. Dehnen and J. J. Binney, Mon. Not. R. Astron. Soc. 298, 387 (1998).
14. C. J. Dolan and R. D. Mathieu, Astron. J. 118, 387 (1999).
15. C. J. Dolan and R. D. Mathieu, Astron. J. 121, 2124 (2001).
16. C. J. Dolan and R. D. Mathieu, Astron. J. 123, 387 (2002).
17. J. Faherty, F. Walter, and J. Anderson, Astrophys. Space Sci. 308, 225 (2007).
18. P.C. Frisch, Nature 364, 395 (1993).
19. B. Fuchs, D. Breitschwerdt, M.A. Avilez, et al., Mon. Not. R. Astron. Soc. 373, 993 (2006).
20. N. Gehrels and W. Chen, Nature 361, 706 (1993).
21. G.A. Gontcharov, Pisma Astron. Zh. 32, 844 (2006) [Astron. Lett. 32, 759 (2006)].
22. J.P. Halpern and S.S. Holt, Nature 357, 222 (1992).
23. J.P. Halpern and M. Ruderman, Astrophys. J. 415, 286 (1993).
24. R. Hoogerwerf, J.H.J. de Bruijne, and P.T. de Zeeuw, Astron. Astrophys. 365, 49 (2001).
25. M.S. Jackson, J.P. Halpern, E. Gotthelf, et al., Astroph. J. 578, 935 (2002).
26. N.V. Kharchenko, A.E. Piskunov, S. S. Röser, et al., Astron. Astrophys. 440, 403 (2005).
27. N.V. Kharchenko, R.-D. Scholz, A.E. Piskunov, et al., Astron. Nachr. 328 (2007).
28. P.G. Kulikovsky, Stellar Astronomy (Nauka, Moscow, 1985) [in Russian].
29. A.D. Kuzmin and V.V. Losovsky, Pisma Astron. Zh. 23, 323 (1997) [Astron. Lett. 23, 283 (1997)].
30. B. Lindblad, Arkiv Mat., Astron., Fysik, Bd. 20 A, 17 (1927).
31. B. Lindblad, Handbuch der Physik 53, 21 (1959).
32. R.J. Maddalena and M. Morris, Astroph. J. 323, 179 (1987).
33. V.M. Malofeev and O.I. Malov, Nature 389, 697 (1997).
34. P.M. McGehee, Astron. J. 131, 2959 (2006).
35. C. Motch, A.M. Pires, F. Haberl, et al., Astrophys. Space Sci. 308, 217 (2006).
36. D. Page, J. M. Lattimer, M. Prakash, et al., Astroph. J. Suppl. Ser. 155, 623 (2004).
37. L.J. Pellizza, R.P. Mignani, I.A. Grenier, et al., Astron. Astrophys. 435, 625 (2005).
38. A.E. Piskunov, E. Schilbach, N.V. Kharchenko, et al., Astron. Astrophys. 477, 165 (2008).
39. S.B. Popov, M. Colpi, M.E. Prokhorov, et al., Astron. Astrophys. 406, 111 (2003).
40. N.A. Sakhibullin, Simulation Methods in Astrophysics (Fan, Kazan, 2003) [in Russian].
41. G. Schaller, D. Schaerer, G. Meynet, et al. Astron. Astrophys. Suppl. Ser. 96, 269 (1992).
42. E. Schilbach and S. S. Röser, astro-ph 0806.0762 (2008).
43. Yu. A. Shibanov, S. Zharikov, V. Komarova, et al., Astron. Astrophys. 448, 313 (2006).
44. V.V. Smith, C. Cunha, and B. Plez, Astron. Astrophys. 281, L41 (1994).
45. van Leeuwen, Astron. Astrophys. 474, 653 (2007).
46. D.G. Yakovlev, K.P. Levenfish, and Yu. A. Shibanov, Usp. Fiz. Nauk 169, 825 (1999) [Phys. Usp. 42, 737 (1999)].
47. A.V. Zasov and K.A. Postnov, General Astrophysics (Fryazino, 2006) [in Russian].
48. The Hipparcos and Tycho Catalogues, ESA SP-1200 (1997).
Fig. 1. Positions of the open clusters in the Ori OB1 association and the Geminga pulsar (the trajectory was computed for a radial velocity of $-100 \text{ km s}^{-1}$).

Fig. 2. (a) Expected distribution of the minimum separation $\Delta r \leq 10 \text{ pc}$ for Geminga encounters with the cluster ASCC21; (b) histogram of encounter times (the time is measured into the past).
Fig. 3. Domains of admissible values for Geminga at which 3137 encounters occur between the pulsar and the cluster ASCC21 to distances $\Delta_r \leq 10$ pc.
Fig. 4. Domains of admissible values for the cluster ASCC21 at which 3137 encounters with the pulsar occur at separations $\Delta r \leq 10$ pc.
Fig. 5. (a) Expected distribution of the minimum separation $\Delta_r \leq 10$ pc for the encounters of HIP 22061 and HIP 29678 within $\Delta_r \leq 50$ pc of the cluster $\lambda$Ori; (b) histogram of encounter times (the time is measured into the past).