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Kinematics of the Scorpius–Centaurus OB Association

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Abstract—A fine structure related to the kinematic peculiarities of three components of the Scorpius–Centaurus association (LCC, UCL, and US) has been revealed in the UV-velocity distribution of Gould Belt stars. We have been able to identify the most likely members of these groups by applying the method of analyzing the two-dimensional probability density function of stellar UV velocities that we developed. A kinematic analysis of the identified structural components has shown that, in general, the center-of-mass motion of the LCC, UCL, and US groups follows the motion characteristic of the Gould Belt, notably its expansion. The entire Scorpius–Centaurus complex is shown to possess a proper expansion with an angular velocity parameter of 46 ± 8 km s^{-1} kpc^{-1} for the kinematic center with $l_0 = -40°$ and $R_0 = 110$ pc found. Based on this velocity, we have estimated the characteristic expansion time of the complex to be 21 ± 4 Myr. The proper rotation velocity of the Scorpius–Centaurus complex is lower in magnitude, is determined less reliably, and depends markedly on the data quality.

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INTRODUCTION

When the first data on the spectral types of luminous stars became available, numerous researchers identified well-defined groups of O and B stars that subsequently, at the suggestion of Ambartsumian (1947), came to be called associations. The hypothesis of a low space density and, as a result, dynamical instability of associations in the field of Galactic tidal forces was also first put forward by Ambartsumian (1949).

As was shown by Blaauw (1952), an expanding association with an initially spherical shape stretches into an ellipse whose orientation changes with time as a result of the Galactic differential rotation.

Scorpius–Centaurus (Sco OB2 or Sco–Cen) is the nearest association. Blaauw (1964) was the first to estimate the kinematic age of this association, ≈20 Myr, by analyzing stellar radial velocities using a linear expansion coefficient $k = 50$ km s^{-1} kpc^{-1}. This age corresponds to the time it takes for a star to traverse the characteristic radius of the region occupied by the association.

Following Blaauw (1964), one identifies three groups in the Scorpius–Centaurus association: US (Upper Scorpius), UCL (Upper Centaurus–Lupus), and LCC (Lower Centaurus–Crux). At present, many authors suggest expanding the list of possible association members. There is indubitable evidence that the recently discovered nearby open clusters β Pic, TWA, Tuc/Hor, η Cha, and ϵ Cha (Mamajek and Feigelson 2001; Song et al. 2003; Mamajek 2005) also belong to the Scorpius–Centaurus association or are part of its loose halo.

The ages of the association members were estimated by de Geus et al. (1989) using data in the Walraven ($VBLUW$) photometric system: 5–6 Myr for US, 14–15 Myr for UCL, and 11–12 Myr for LCC. The current age estimates for the association members obtained by comparing the evolutionary tracks of stars with their positions in the Hertzsprung–Russell diagram (Mamajek et al. 2002; Sartori et al. 2003) are 8–10 Myr for US and 16–20 Myr for UCL and LCC.

Based on their analysis of data from the the Hipparcos Catalog (1997) by the spaghetti method, de Zeeuw et al. (1999) compiled a list of likely Scorpius–Centaurus members and determined their mean distances: 145 ± 2 pc to US, 140 ± 2 pc to UCL, and 118 ± 2 pc to LCC.

A considerable number of low-mass late-type pre-main-sequence stars with ages of several million years have been revealed in the Scorpius–Centaurus

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association by several characteristic signatures (lithium overabundance, X-ray emission, etc.) (Preibish and Zinnecker 1999; Mamajek et al. 2002; Sartori et al. 2003). There are both radial velocities and proper motions for some of these stars (Makarov 2003; Mamajek et al. 2002; Mamajek 2005; Torres et al. 2006).

In the opinion of Preibisch and Zinnecker (1999), the star formation process in the Scorpius–Centaurus association finished about a million years ago; it contains no significant (in mass) reserves of dust, since its visual extinction is low ($A_V \leq 2^m$), and of gas, which was swept up to the periphery of the region after supernova explosions. This is an important argument that the association is gravitationally unbound.

There are strong grounds for believing that the nearby OB associations and, in particular, the Scorpius–Centaurus association, are members of the Gould Belt (Lindblad et al. 1973; de Zeeuw et al. 1999; Bobylev 2006).

A critical review of the formation scenarios for the Scorpius–Centaurus association can be found in Sartori et al. (2003). These authors considered the model of successive star formation (Blaauw 1964, 1991; Preibisch and Zinnecker 1999), the Gould Belt model (Lindblad et al. 1973; Olano 1982), and the model of star formation by infall of high-velocity clouds on the Galactic disk (Lépine and Duvert 1994) and provided arguments for the model related to the passage of a spiral arm near the Sun.

The goal of this paper is to refine the structure of the Scorpius–Centaurus association and to determine its expansion and rotation velocities from currently available observational data.

INPUT DATA

Dravins et al. (1999), de Bruijne (1999), Lindegren et al. (2000), and Madsen et al. (2002) showed that the individual distances for stars of nearby open clusters, such as the Hyades, could be determined by the well-known moving cluster method more accurately than from Hipparcos parallaxes. The moving cluster method for stars of the Scorpius–Centaurus association was used to determine "improved" individual distances (de Bruijne 1999) and "improved astrometric" radial velocities (Madsen et al. 2002). Monte Carlo simulations (de Bruijne 1999) showed that the expansion/contraction of an association affects significantly the radial velocity determinations and, to a lesser extent, the bias of stellar distance estimators. The radial velocities determined by Madsen et al. (2002) for a large number of stars in the Scorpius–Centaurus association (~500 stars) from the list by de Zeeuw et al. (1999) are of interest to us as a highly accurate ephemeris.

There is a list of 700 Hipparcos stars with measured radial velocities belonging to the Gould Belt at our disposal. Its description can be found in our previous papers (Bobylev 2004b, 2006). For the next series of Scorpius–Centaurus stars, we made a number of additions when new data became available:

(a) for the classical members of the Scorpius–Centaurus association (UCL, LCC, and US), the list of candidates was taken from de Zeeuw et al. (1999), which was expanded to include a number of stars from the list by de Geus et al. (1989);

(b) for the β Pic cluster, the new data were taken from Torres et al. (2006);

(c) For the TWA cluster, the data were taken from Mamajek (2005); in this paper, we use only five stars of this cluster with measured trigonometric parallaxes—TWA 1, 4, 9, 11, and 19;

(d) the list of candidates of the Chamaeleon open cluster, which also includes the small known η Cha and ϵ Cha clusters, was taken from Sartori et al. (2003).

The OSACA (Bobylev et al. 2006) and PCRV (Gontcharov 2006) catalogs served as the main sources of stellar radial velocities. The main peculiarity of these catalogs is that they were reduced to the same radial velocity standard proposed by Gontcharov. The difference between these two versions is that the OSACA catalog includes the "astrometric" radial velocities of Scorpius–Centaurus stars from Madsen et al. (2002), while these were not used in compiling the PCRV catalog.

For several members of the Scorpius–Centaurus association (UCL, LCC, and US), we calculated new stellar radial velocities based on the PCRV catalog (Gontcharov 2006) and the paper by Jilinski et al. (2006). No stars with a random error in the radial velocity larger than 5 km s^{-1} were used. We designate the stellar space velocities calculated using the radial velocities from these catalogs as "real" to distinguish them from those calculated using the "astrometric" radial velocities from Madsen et al. (2002).

As the stellar distance estimates, we use only the Hipparcos trigonometric parallaxes. We use only those stars that satisfy the condition $e_\pi/\pi < 0.2$, which allows the influence of the well-known Lutz–Kelker effect (Lutz and Kelker 1973) to be reduced.

We took into account the Galactic rotation using the Oort constants $A = 13.7 \pm 0.6$ km s^{-1} kpc^{-1} and $B = -12.9 \pm 0.4$ km s^{-1} kpc^{-1} determined previously (Bobylev 2004a).

Figure 1 shows the distribution of UV velocities corrected for the Galactic rotation for the stars that satisfy the condition $e_\pi/\pi < 0.2$. Figure 1a presents the UV velocities of 255 Gould Belt stars; only the "real" data were used to calculate the space velocities. Figure 1b presents the UV velocities of 380 Scorpius–Centaurus stars whose radial velocities were taken from the catalog by Madsen et al. (2002). As can be seen from Fig. 1b, three groups of stars related to the kinematic peculiarities of UCL, LCC, and US are clearly identified. In Fig. 1a, this separation into three isolated fractions is less distinct.

Below, we set the goal of separating the Scorpius–Centaurus structure from the overall distribution of UV velocities for the Gould Belt based on the "real" data.

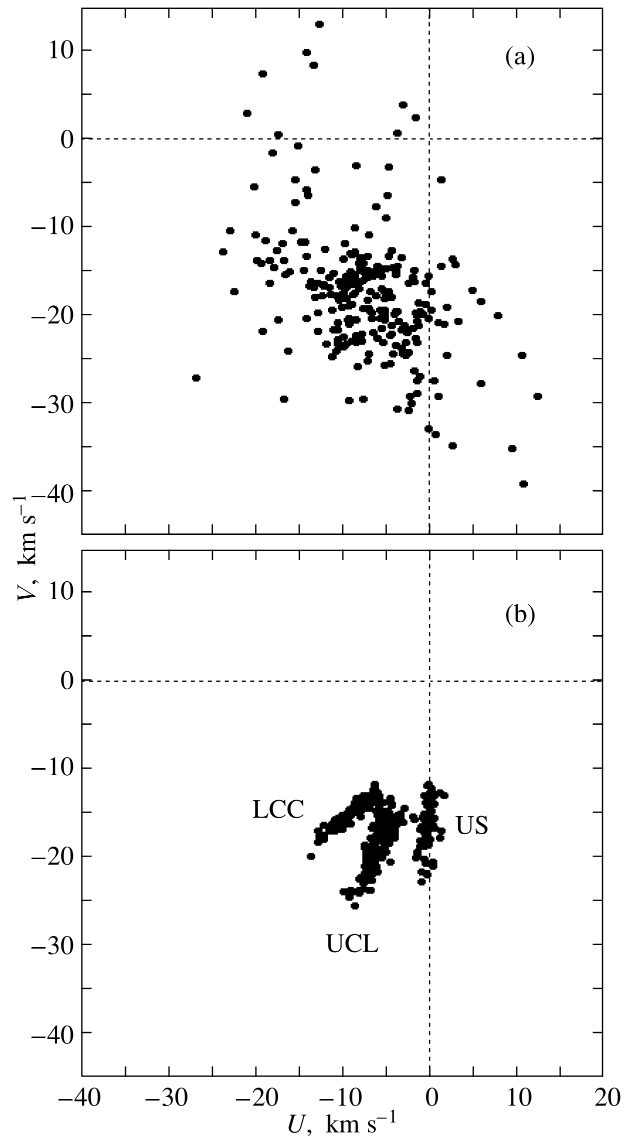

Fig. 1. (a) UV velocities of 255 Gould Belt stars ("real" data); (b) UV velocities of 380 Scorpius–Centaurus stars whose radial velocities were taken from the catalog by Madsen et al. (2002). The stellar velocities were corrected for the Galactic rotation and are given relative to the Sun.

METHODS AND APPROACHES

The Kinematic Model

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).

We apply the equations derived from Bottlinger's standard formulas (Ogorodnikov 1965) by assuming the existence of a common kinematic center for rotation and expansion using two terms of the Taylor expansion of the angular velocity for rotation ω and the analogous parameter for expansion k (Lindblad 2000; Bobylev 2004b). The conditional equations are

$$\begin{aligned} V_r = {} & -U_0 \cos b \cos l - V_0 \cos b \sin l \\ & - W_0 \sin b + \cos^2 b k_0 r \\ & + (R - R_0)[r \cos b - R_0 \cos(l - l_0)] \cos b k'_0 \\ & - R_0(R - R_0) \sin(l - l_0) \cos b \omega'_0, \end{aligned} \quad (1)$$

$$\begin{aligned} V_l = {} & U_0 \sin l - V_0 \cos l \\ & - (R - R_0)[R_0 \cos(l - l_0) - r \cos b]\omega'_0 \\ & + r \cos b \omega_0 + R_0(R - R_0) \sin(l - l_0) k'_0, \end{aligned} \quad (2)$$

$$\begin{aligned} V_b = {} & U_0 \cos l \sin b \\ & + V_0 \sin l \sin b - W_0 \cos b - \cos b \sin b k_0 r \\ & - (R - R_0)[r \cos b - R_0 \cos(l - l_0)] \sin b k'_0 \\ & + R_0(R - R_0) \sin(l - l_0) \sin b \omega'_0. \end{aligned} \quad (3)$$

Here, V_r is the stellar radial velocity, $V_l = 4.74 r \mu_l \cos b$, $V_b = 4.74 r \mu_b$, the coefficient 4.74 is the quotient of the number of kilometers in an astronomical unit by the number of seconds in a tropical year, $r = 1/\pi$ is the heliocentric distance of the star, the stellar proper motion components $\mu_l \cos b$ and μ_b are in mas yr^{-1}, the radial velocity V_r is in km s^{-1}, the parallax π is in mas, U_0, V_0, W_0 are the stellar centroid velocity components relative to the Sun, R_0 is the distance from the Sun to the kinematic center, R is the distance from the star to the center of rotation, l_0 is the direction of the kinematic center, R, R_0, and r are in kpc. The quantity ω_0 is the angular velocity of rotation and k_0 is the radial expansion/contraction velocity of the stellar system at distance R_0; the parameters ω'_0 and k'_0 are the corresponding derivatives. The distance R can be calculated using the expression

$$R^2 = (r \cos b)^2 - 2R_0 r \cos b \cos(l - l_0) + R_0^2.$$

The system of conditional equations (1)–(3) con-

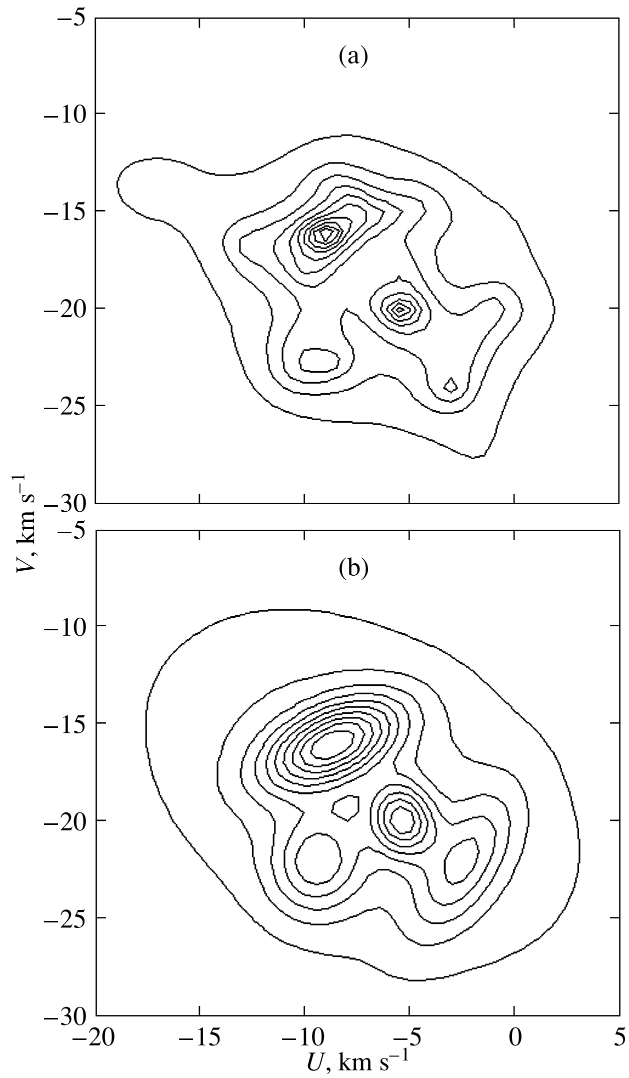

Fig. 2. (a) Probability density distribution obtained by the adaptive kernel method from a given discrete distribution of stellar UV velocities; (b) distribution obtained by approximating the UV velocity distributions of stars of individual fractions by individual Gaussians.

tains seven unknowns: U_0, V_0, W_0, ω_0, ω'_0, k_0, and k'_0, to be determined by the least-squares method. Equations (1)–(3) are written in such a way that the rotation from the x axis to the y axis is considered positive.

The Method for Separating Stellar Fractions

In this paper, we develop a variety of the probabilistic approach to separating stellar fractions based on the approximation of the two-dimensional probability density function of the UV velocities of all the stars under consideration by a set of individual Gaussians that represent the probability densities of individual structural features.

To estimate the two-dimensional probability density $f(U,V)$ for all the stars under consideration, we apply an adaptive kernel method (Skuljan et al. 1999) to the map of initial, discretely distributed space UV velocities. In contrast to Skuljan et al. (1999), we use a two-dimensional, radially symmetric Gaussian kernel function:

$$K(r) = \frac{1}{\sqrt{2\pi\sigma}} \exp - \left(\frac{r^2}{2\sigma^2}\right),$$

where $r^2 = x^2 + y^2$. Obviously, the relation $\int K(r)dr = 1$ needed to estimate the probability density holds. Note that, in our case, the bin size of the two-dimensional maps was chosen to be 0.25 km s^{-1}, given the density of star distribution in the velocity field; the area of a square bin was $S = 0.25 \times 0.25$ km^2 s^{-2}.

The main idea of the adaptive kernel method is that a convolution with a kernel whose width is specified by a parameter σ that changes with the data density near a given point is performed at each point of the map. Thus, in zones with an enhanced density, the smoothing is performed with a relatively narrow kernel.

We use the following definition of the adaptive kernel estimator at an arbitrary point $\xi = (U,V)$ (Skuljan et al. 1999):

$$\hat{f}(\xi) = \frac{1}{n}\sum_{i=1}^{n} K\left(\frac{\xi - \xi_i}{h\Lambda_i}\right),$$

where $\xi_i = (U_i, V_i)$, Λ_i is the local dimensionless bandwidth factor at point ξ_i, h is a general smoothing parameter, and n is the number of data points $\xi_i = (U_i, V_i)$. The local bandwidth factor Λ_i at each point of the two-dimensional UV plane is defined by

$$\Lambda_i = \sqrt{\frac{g}{\hat{f}(\xi)}},$$

$$\log g = \frac{1}{n}\sum_{i=1}^{n} \ln \hat{f}(\xi),$$

where g is the geometric mean of $\hat{f}(\xi)$. Obviously, to compute Λ_i, we need the distribution estimate $f(\xi)$, which, in turn, can be computed only when all Λ_i are known. Therefore, the problem of finding the sought-for distribution can be solved iteratively. As the first approximation, we use the distribution obtained by smoothing the initial UV map with a fixed kernel. An optimal value for the smoothing parameter h is determined by minimizing the rms deviation of the $\hat{f}(\xi)$ estimate from the true distribution $f(\xi)$. The value of h that we found for the complex of stars considered here is about 1.25 km s^{-1}. In addition, the

Table 1. Data on Gould Belt stars

HIP	Cluster	V_r, km s^{-1}	e_{V_r}	i	Source	$P^{\rm LCC}$	$P^{\rm UCL}$	$P^{\rm US}$	$P^{\rm Gould}$	...
1	2	3	4	5	6	7	8	9	10	...
50520	LCC	15.8	0.7	2	PCRV	0.06	0.22	0.00	0.72	...
50847	LCC	12.0	4.2	1	PCRV	0.73	0.00	0.00	0.27	...
53701	LCC	15.7	4.3	1	PCRV	0.00	0.69	0.00	0.31	...
55425	LCC	26.8	2.7	1	Jilinski	0.00	0.00	0.00	1.00	...
56561	LCC	−1.1	2.5	2	PCRV	0.00	0.00	0.00	1.00	...
57851	LCC	20.0	2.0	2	P+Jil	0.00	0.00	0.50	0.50	...
58867	gLCC	−8.9	0.5	1	Jilinski	0.00	0.00	0.00	1.00	...
...	...	...	...	...	...	...	...	...	...	...

Note. $e_\pi/\pi < 0.2$, Table 1 is fully accessible in electronic form.

maps are scaled by the factor nS to obtain the total probability equal to unity.

Our two-dimensional probability density map of stellar UV velocities (derived from the data of Fig. 1a) is presented in Fig. 2a. In this figure, we can visually identify the distributions of LCC, UCL, and US stars and an extended component of the Gould Belt. Although the distributions of LCC, UCL, and US stars in Fig. 2a are less isolated than those in Fig. 1b, in general, we can see a similarity in structure between the UV velocity planes constructed using fundamentally different (with regard to the stellar radial velocities) data.

With the goal of a formally justified assignment of each star from the complex under consideration to a particular fraction, we approximate each fraction by a set of Gaussians, each of which is represented by six unknown parameters:

$$P_i(U,V) = A_i \exp \times \left\{ -\frac{[(U-U_{0i})\cos\theta_i + (V-V_{0i})\sin\theta_i]^2}{2\sigma_{Ui}^2} - \frac{[(U-U_{0i})\sin\theta_i - (V-V_{0i})\cos\theta_i]^2}{2\sigma_{Vi}^2} \right\},$$

where i is the Gaussian number, $P_i(U,V)$ is the corresponding distribution function, A_i is the amplitude proportional to the number of stars in the fraction, U_{0i} and V_{0i} are the U and V coordinates of the Gaussian center, respectively, σ_{Ui} and σ_{Vi} are the corresponding dispersions of the distribution, and θ_i is the angle defining the Gaussian orientation in the UV plane (the angle between the major axis of the ellipse and the V axis).

In the general case, we represent the LCC fraction by the sum of $N^{\rm LCC}$ Gaussians, the UCL fraction by the sum of $N^{\rm UCL}$ Gaussians, the US fraction by the sum of $N^{\rm US}$ Gaussians, and, finally, the overall extended parts of the Gould Belt referring to the entire complex of stars by the sum of $N^{\rm Gould}$ Gaussians. Denote the set of numbers of the Gaussians approximating the LCC, UCL, US fractions and the extended parts of the Gould Belt by $N_{\rm LCC}$, $N_{\rm UCL}$, $N_{\rm US}$, and $N_{\rm Gould}$, respectively. Next, we add all Gaussian $N = N^{\rm UCL} + N^{\rm UCL} + N^{\rm US} + N^{\rm Gould}$ to obtain the model distribution

$$P_{\rm M}(U,V) = \sum_{i=1}^{N} P_i(U,V),$$

with $6N$ unknown parameters. To determine them, we apply the least-squares method to bring the model distribution closer to that obtained from the initial stellar velocity distribution (Fig. 2a). Thus, we minimize the functional

$$e = \sum_{U,V} ||f(U,V) - P_M(U,V)||^2.$$

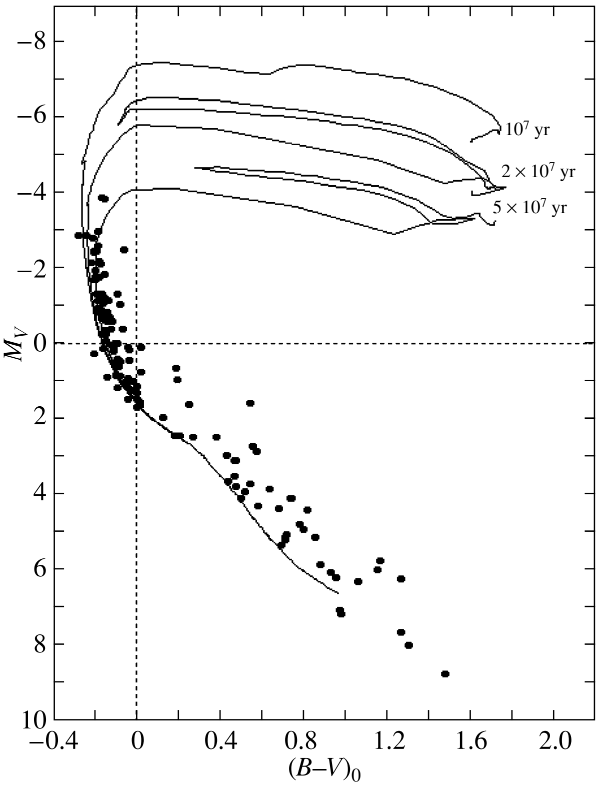

Fig. 3. Color–absolute magnitude diagram for 134 Scorpius–Centaurus stars that satisfy the condition $e_\pi/\pi < 0.15$.

Next, we calculate the probabilities that each star with number $k = 1, 2, \ldots, n$ belongs to ones of the LCC, UCL, and US structures or the extended part of the Gould Belt using the formulas

$$P_k = \sum_{i=1}^{N} P_i(U_k, V_k), \qquad (4)$$

$$P_k^{\rm LCC} = \left(\sum_{i\in N_{\rm LCC}} P_i(U_k, V_k)\right) \Big/ P_k,$$

$$P_k^{\rm UCL} = \left(\sum_{i\in N_{\rm UCL}} P_i(U_k, V_k)\right) \Big/ P_k,$$

$$P_k^{\rm US} = \left(\sum_{i\in N_{\rm US}} P_i(U_k, V_k)\right) \Big/ P_k,$$

$$P_k^{\rm Gould} = \left(\sum_{i\in N_{\rm Gould}} P_i(U_k, V_k)\right) \Big/ P_k.$$

Obviously, the maximum of the calculated probabilities assigns a star to a particular stellar fraction whose name is given as the superscript in the above formulas.

In our case, having solved the minimization problem at $N_{\rm LCC} = 1$, $N_{\rm UCL} = 2$, $N_{\rm US} = 1$, and $N_{\rm Gould} = 1$, we found a model distribution shown in Fig. 2b. The approximation error is 4.4%. A higher accuracy can be achieved by including more Gaussians approximating even finer structural features in the UV distribution.

RESULTS

The columns of Table 1 give the following: (1) the Hipparcos (1997) star number; (2) the cluster name, the letter g for US, UCL, and LCC marks the stars from the list by de Geus (1989); (3) the radial velocity; (4) the random error in the radial velocity; (5) the number of catalogs used to calculate the mean radial velocity; (6) a reference to the radial velocity source; (7)–(10) the probabilities $P^{\rm LCC}$, $P^{\rm UCL}$, $P^{\rm US}$, and $P^{\rm Gould}$ that we calculated using Eqs. (4).

Table 1 is fully accessible in electronic form. In the electronic version of the table, columns 11–20 give the parallaxes, coordinates, proper motions, and photometric magnitudes copied from the Hipparcos Catalog (1997) and the stellar space velocities U, V, W that we calculated. In all, it contains data on 255 stars satisfying the condition $e_\pi/\pi < 0.2$ that served as a basis for constructing Figs. 1a and 2.

Practice has shown that the condition $P^{\rm Gould} < 1.0$ effectively separates the background stars (in our case, those of the Gould Belt) from the overall distribution of Scorpius–Centaurus stars. We use this condition below.

To reduce the influence of the Lutz–Kelker effect (Lutz and Kelker 1973), below we use only the stars that satisfy the condition $e_\pi/\pi < 0.15$.

The Hertzsprung–Russell Diagram

Figure 3 shows the color–absolute magnitude diagram for 134 stars, $e_\pi/\pi < 0.15$. The isochrones for three ages constructed from the data by Schaller et al. (1992) for metallicity $Z = 0.02$ are shown. To take into account the interstellar extinction, we used the A_V estimates from Sartori et al. (2003) and de Bruijne (1999). To pass from the Tycho photometric magnitudes $V_{\rm T}$ and $B_{\rm T}$ to the Johnson system and to determine V and $B-V$, we used the polynomials from Mamajek et al. (2002).

In accordance with the constructed diagram, we excluded several stars in the list by de Zeeuw et al. (1999) belonging to the horizontal giant branch from the list of candidates following the recommendations by Sartori et al. (2003) and Mamajek et al. (2002).

Table 2. Kinematic parameters of the Scorpius–Centaurus association

No.	$-U_0$	$-V_0$	$-W_0$	ω_0	ω_0'	k_0	k_0'	σ_0	$N_\star$
1	$-11.8_{(0.8)}$	$-18.2_{(0.8)}$	$-6.1_{(0.3)}$	$20_{(8)}$	$481_{(192)}$	$40_{(8)}$	$-171_{(192)}$	2.9	134
2	$-11.2_{(0.8)}$	$-18.4_{(0.8)}$	$-6.1_{(0.3)}$	$29_{(8)}$	$421_{(193)}$	$46_{(8)}$	$17_{(193)}$	2.9	134
3	$-11.2_{(0.8)}$	$-18.6_{(0.8)}$	$-6.1_{(0.3)}$	$38_{(8)}$	$356_{(195)}$	$34_{(8)}$	$14_{(195)}$	2.9	134
2a	$-8.0_{(1.3)}$	$-8.3_{(1.3)}$	$-6.1_{(0.1)}$	$-56_{(8)}$	$125_{(136)}$	$41_{(8)}$	$135_{(136)}$	1.7	279
2b	$-8.2_{(1.2)}$	$-9.3_{(1.2)}$	$-6.5_{(0.2)}$	$-40_{(11)}$	$232_{(200)}$	$39_{(12)}$	$347_{(183)}$	1.7	279

Note. U_0, V_0, W_0, and σ_0 are in km s^{-1}, ω_0 and k_0 are in km s^{-1} kpc^{-1}, ω_0' and k_0' are in km s^{-1} kpc^{-2}, $N_\star$ is the number of stars used, all quantities were determined with the parameters of the center $l_0 = -40°$ and $R_0 = 110$ pc, σ_0 is the error of a unit weight found when solving the system of equations (1)–(3).

The Spatial Structure of the Association

Given the satisfaction of all the above conditions and restrictions, apart from the classical LCC, UCL, and US members (a total of 90 stars), the association of 134 stars includes 44 stars belonging to the following clusters: β Pic (20 ± 10 Myr; Barrado y Navascués et al. 1999)—16 stars; nearby X-ray stars from the lists by Makarov (2003)—9 stars and Wichmann et al. (2003)—1 star (HIP 58996); TWA ($\approx$10 Myr; Mamajek et al. 2000)—5 stars; Tuc/Hor ($\approx$30 Myr; Torres et al. 2000; Zuckerman et al. 2001)—5 stars; α Car—4 stars; Cha—3 stars; and IC 2602—1 star (HIP 52370).

We believe that one star of the compact open cluster IC 2602 ($\approx$30 Myr; Luhman 2001) could have been included in the sample by chance due to the dispersion of errors in the space velocities.

Table 1 includes eight stars of the Chamaeleon cluster, most of which have $P^{\rm Gould}$ close to unity. Only for two stars, HIP 42637 (η Cha, 8 Myr; Mamajek et al. 1999) and HIP 58484 (ϵ Cha, 5–15 Myr; Mamajek et al. 2000), did we obtain noticeable values of $P^{\rm LCC} \approx P^{\rm UCL} \approx 0.2$. We may conclude that the expansion of the stellar composition of the Chamaeleon cluster suggested by Sartori et al. (2003) was performed by including stars from the loose halo of the Scorpius–Centaurus association and stars belonging to the Gould Belt structure.

The fact that we obtained high probabilities, $P^{\rm LCC} \approx 0.5$ or $P^{\rm UCL} \approx 0.5$, for several stars of the relatively old open cluster α Car ("Platais 8," 56 Myr; Piskunov et al. 2006) is of considerable interest.

Our list of stars belonging to the Scorpius–Centaurus association agrees with the list by Fernández et al. (2006). Based on the epicyclic approximation, these authors showed that 10–20 Myr ago, the separation between the LCC center and such clusters as β Pic, TWA, Tuc/Hor, η Cha, and ϵ Cha was at a minimum, being several tens of parsecs.

The total number of "real" stars is approximately equal to the number of stars with available high-precision radial velocities (the database has not yet been published) in the list by Fuchs et al. (2006) (79 classical members of the Scorpius–Centaurus association).

The Expansion and Rotation of the Association

Table 2 lists the kinematic parameters that we found from the solution of Eqs. (1)–(3) using only those Scorpius–Centaurus stars for which the condition $e_\pi/\pi < 0.15$ was satisfied. The U_0, V_0, W_0 coordinates listed in the table are given with the opposite sign for the convenience of their comparison with the data in Figs. 1 and 2.

The parameters in the upper part of the table (solutions nos. 1, 2, 3) were found from the "real" data. The parameters in the lower part of the table (solutions nos. 2a and 2b) were found from the data by Madsen et al. (2002). Solution no. 2b was obtained without using stellar radial velocities—from the simultaneous solution of only two equations, (2) and (3). As can be seen from the table, there are no significant differences between solutions nos. 2a and 2b.

Solution no. 1 was obtained from the stellar velocities without any corrections being applied.

Solutions no. 2 were obtained from the stellar velocities corrected for the differential rotation of the Galaxy.

For solution no. 3, the stellar velocities were corrected both for the Galactic rotation and for the motion (rotation and expansion) of the Gould

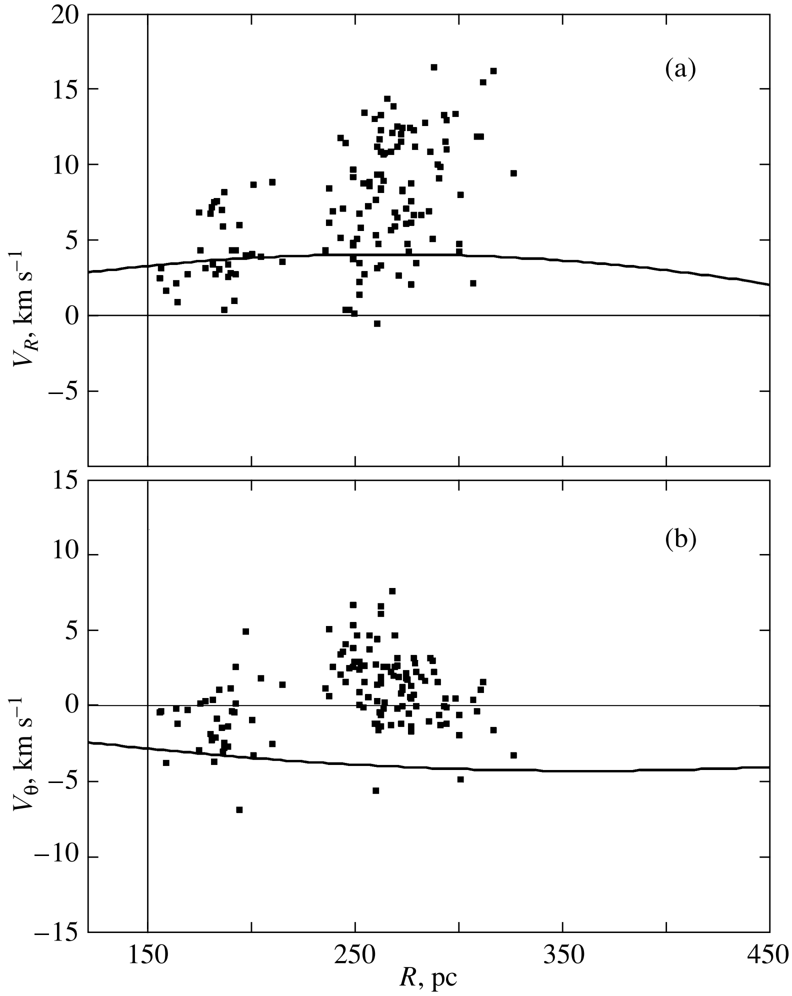

Fig. 4. Expansion, V_R (a), and rotation, V_θ (b), velocities versus distance R from the kinematic center of the Gould Belt calculated at $l_0 = 128°$ and $R_0 = 150$ pc; the vertical line marks R_0.

Belt. For this purpose, we place the kinematic center of the Gould Belt at the point with $l_0 = 128°$ and $R_0 = 150$ pc (Bobylev 2004b) and use $\omega_0 = -19 \pm 5$ km s^{-1} kpc^{-1}, $\omega'_0 = 33 \pm 16$ km s^{-1} kpc^{-2}, $k_0 = 22 \pm 5$ km s^{-1} kpc^{-1}, and $k'_0 = -58 \pm 16$ km s^{-1} kpc^{-2} found by analyzing the motions of the open clusters belonging to the Gould Belt structure (Bobylev 2006).

In Fig. 4, the expansion, V_R, and rotation, V_θ, velocities of the selected 134 stars are plotted against distance R from the kinematic center of the Gould Belt calculated at $l_0 = 128°$ and $R_0 = 150$ pc. The velocities were reduced to the center of mass of the Gould Belt. The plots show the expansion and rotation curves for the Gould Belt that we found from the data on open clusters (Bobylev 2006).

The parameters of the kinematic center l_0 and R_0 must be known to determine the proper rotation and expansion parameters for the association from Eqs. (1)–(3). As the first approximation, we assume that the direction of the kinematic center of the association is close to that of its geometrical center $l_0 \approx -45°$, which we then refine. The results of solving Eqs. (1)–(3) obtained at fixed $l_0 = -45°$ and at various R are presented in Fig. 5. As can be seen from the figure, the derivative of the expansion velocity k'_0 is equal to zero at $R_0 = 110$ pc. Similarly, having fixed R_0 and varying l_0, we found a new approximation, $l_0 = -40°$.

Figure 6 presents the space velocities of 134 stars projected onto the radial (away from the association center) and tangential directions. The velocities were decomposed with the parameters of the center $l_0 = -40°$ and $R_0 = 110$ pc. The velocities were reduced to the center of mass of the association (based on the data of Table 2). The plots show the straight lines that were constructed with $k_0 = 46$ km s^{-1} kpc^{-1} for the linear expansion coefficient

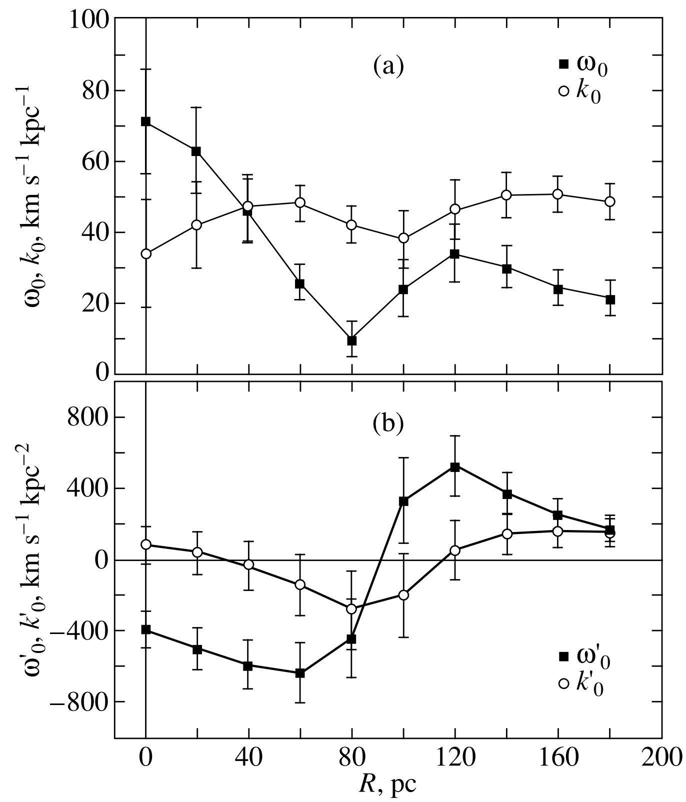

Fig. 5. (a) Parameters of the angular velocities of rotation and expansion for the Scorpius–Centaurus association and (b) the corresponding derivatives versus distance from the kinematic center of the association calculated at $l_0 = -45°$.

and $\omega_0 = 29$ km s^{-1} kpc^{-1} for the angular velocity of rotation found in solution no. 2 of Table 2.

Thus, having a fairly complex model (Eqs. (1)–(3)), we used the derivatives k_0' and ω_0' found, which are determined with large errors, to improve the parameters of the kinematic center and, in the long run, reduce the problem to the linear case. As can be seen from Fig. 6a, the data are described well by the linear expansion coefficient. The rotation is of lesser interest to us, because ω_0 (Fig. 5) is almost always smaller and less stable than k_0.

Figure 7 is similar to Fig. 4, but here we use the velocities of 489 ($e_\pi/\pi < 0.5$) Scorpius–Centaurus stars (only the classical members of the association from the list by de Zeeuw et al. (1999)), whose radial velocities were taken from the catalog by Madsen et al. (2002). The main difference between Figs. 7 and 4 is related to the velocity V_θ. As can be seen from Fig. 7b, a distinct and fairly symmetric crowding of stars is observed at $R < 300$ pc; just as in Fig. 4, the center of this distribution deviates noticeably from the rotation curve of the Gould Belt. At $R > 300$ pc, the distribution of stars has a different pattern—they fall nicely on the rotation curve of the Gould Belt. In our opinion, an appreciable fraction of the stars from the list by de Zeeuw et al. (1999) do not belong to the Scorpius–Centaurus association; they fell into the sample by chance. It may also be concluded that the negative sign of ω_0 (solutions nos. 2a and 2b in Table 2) that we found from the data by Madsen et al. (2002) does not reflect the essence of the real rotation of the association, but is related to the peculiarity of the sample of these stars.

The data obtained lead us to conclude that the Scorpius–Centaurus complex is involved in the systematic expansion of the Gould Belt. On the other hand, there is a proper expansion (solution no. 2 in Table 2) with an angular velocity $k_0 = 46 \pm 8$ km s^{-1} kpc^{-1}. Using the velocity k_0 obtained, we can estimate the characteristic expansion time of the complex from the well-known formula $T = 977.5/k_0$ (Murray 1983), which is $T = 21 \pm 4$ Myr and is an independent kinematic estimate of the age for the Scorpius–Centaurus complex. This value is in good agreement with the estimate of $T = 16$–20 Myr for the age of the oldest LCC and UCL groups obtained by Sartori et al. (2003) from the analysis of photometric data.

Based on the velocity $k_0 = 39 \pm 12$ km s^{-1} kpc^{-1} (solution no. 2b in Table 2) found without using stellar

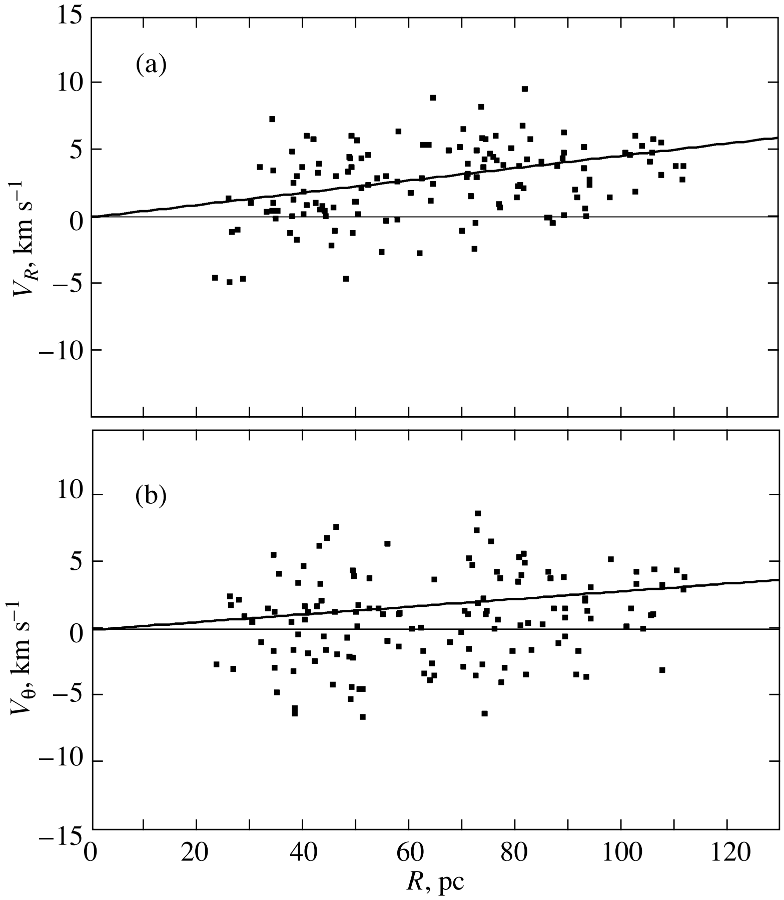

Fig. 6. Expansion, V_R (a), and rotation, V_θ (b), velocities versus distance R from the kinematic center of the Scorpius–Centaurus association calculated at $l_0 = -40°$ and $R_0 = 110$ pc; the vertical line marks R_0.

radial velocities, we obtain a longer expansion time of the complex, $T = 25 \pm 8$ Myr, which agrees, within the 1σ error limits, with the value obtained from the three observed velocity components.

DISCUSSION

We obtained contradictory data on the direction of rotation of the association. Analysis of the motion of the Scorpius–Centaurus association in the field of attraction of the Galaxy modeled in the epicyclic approximation by Breitschwerdt and Avillez (2006) and Fuchs et al. (2006) leads us to conclude that the observed rotation most likely must have the positive sign. On this basis, we conclude that the results obtained using the "real" data are preferred.

The linear expansion coefficient that we found for the Scorpius–Centaurus association, $k_0 = 46 \pm 8$ km s^{-1} kpc^{-1}, is in good agreement with $k_0 = 50$ km s^{-1} kpc^{-1} obtained by Blaauw (1964) from the analysis of stellar radial velocities. Having analyzed the radial velocities of 19 most likely members of the TWA cluster by Blaauw's method, Mamajek (2005) found $k_0 = 49 \pm 27$ km s^{-1} kpc^{-1}. For the members of the moving cluster β Pic (about 40 stars), Torres et al. (2006) found a dependence of the velocity U on the x coordinate with a coefficient of 53 km s^{-1} kpc^{-1}, which is interpreted as the expansion parameter of this cluster.

A whole system of cold molecular clouds such as R CrA, Lupus, Chamaeleon–Muska, and Coalsack, is known in a wide neighborhood of the Scorpius–Centaurus association (Corradi et al. 2004). The analysis by Corradi et al. (2004) revealed an outflow of gas (a component located at a distance $d \le 60$ pc) from the Scorpius–Centaurus association toward the Sun with a velocity of -7 km s^{-1}. This is in good agreement with the expansion model of the Scorpius–Centaurus complex.

Fernández et al. (2006) showed that the onset of star formation in the Scorpius–Centaurus complex could be related to the passage of a giant molecular cloud through a spiral arm ~30 Myr ago. The authors believe that the model requires no contraction of the

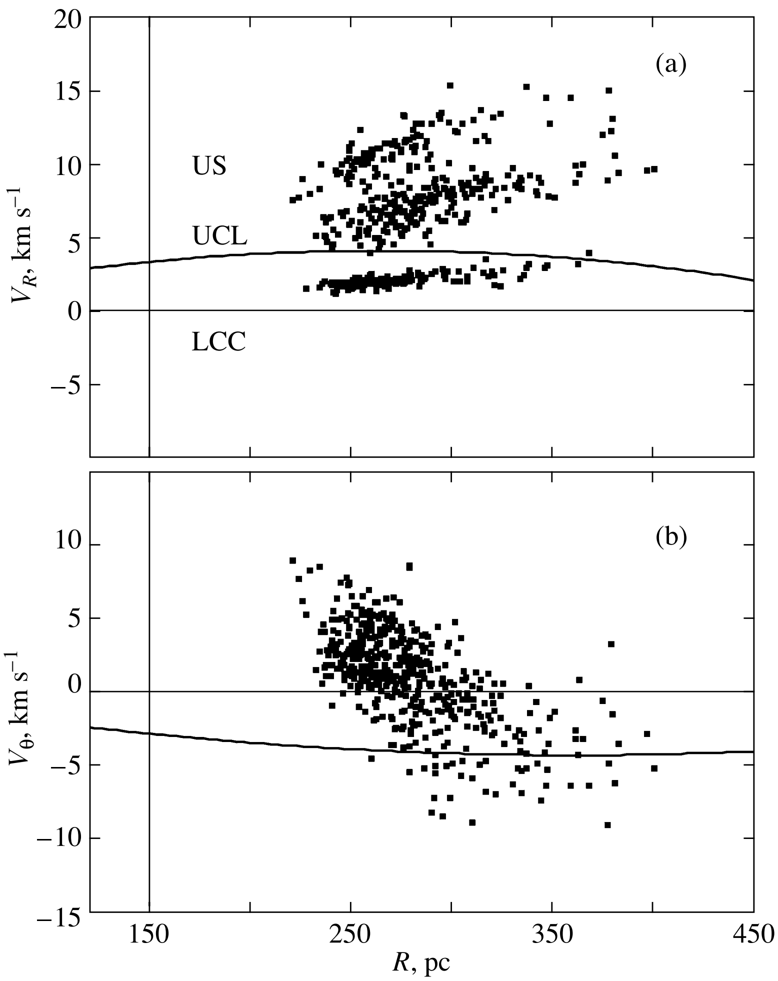

Fig. 7. Expansion, V_R (a), and rotation, V_θ (b), velocities of 489 Scorpius–Centaurus stars whose radial velocities were taken from the catalog by Madsen et al. (2002) versus distance R from the kinematic center of the Gould Belt calculated at $l_0 = 128°$ and $R_0 = 150$ pc; the vertical line marks R_0.

entire cloud and that the onset of star formation in a small region of the cloud with the highest pressure served as a triggering mechanism. In the coordinate system associated with the Local Standard of Rest, the parent cloud was in the first Galactic quadrant and had coordinates $x \approx 100$ pc and $y \approx 100$ pc (the directions are indicated in our coordinate system). This model depends strongly on the assumed pattern speed, which is presently known with an insufficient accuracy (Melnik et al. 2001; Popova and Loktin 2005).

In the opinion of Breitschwerdt and Avillez (2006), supernova explosions in the Scorpius–Centaurus association are responsible for the presence of two regions of hot coronal gas—the Local and Loop I Bubbles. It was concluded that the number of supernova explosions needed for the formation of the Local Bubble was 14–20.

Based on the epicyclic approximation, Fuchs et al. (2006) showed that the separation between the LCC, UCL, and US centers and the Local Bubble was at a minimum 10–15 Myr ago.

Comparison of the UV-distributions for 302 Hipparcos stars associated with the Scorpius–Centaurus association presented in Fig. 3 from Fuchs et al. (2006) and Figs. 1 and 2 in this paper shows a similarity in that the distribution ellipse is oriented at an angle of about 45°, which is attributable to the expansion of the complex.

The theory of successive star formation (Blaauw 1964, 1991) runs into the difficulty that the Scorpius–Centaurus association exhibits no noticeable gradient in stellar ages as a function of the distance (the distance from the supernova). To eliminate this peculiarity, Preibisch and Zinnecker (1999) assumed for US that the stars were formed during a short time interval. The structure of the UV–velocity distribution consisting of three fairly isolated, approximately parallel branches that we found leads us to conclude that there were three periods of star formation separated by short time intervals in the expanding Scorpius–Centaurus complex. We believe that this conclusion is consistent with the conclusions by Preibisch and Zinnecker (1999).

CONCLUSIONS

We considered the list of Hipparcos stars belonging to the Scorpius–Centaurus association with measured parallaxes, proper motions, and radial velocities.

Three characteristic features related to the kinematic peculiarities of the LCC, UCL, and US groups were revealed in the UV-velocity distribution of Gould Belt stars. A method for analyzing the UV plane was developed to separate them from the Gould Belt stars. Applying this method allowed us to identify the most likely members of these features.

We believe the results obtained using the "real" data to be most reliable. The stellar radial velocities calculated by the moving cluster method from Madsen et al. (2002) have small random errors. However, the list of candidates for Scorpius–Centaurus members by de Zeeuw et al. (1999) probably contains a considerable number of background stars (notably for distant stars farther than 150 pc from the Sun) and needs to be corrected. We used a method for separating the association members from the Gould Belt distribution that is free from any initial assumptions about the membership of stars in this association to a much larger degree than the moving cluster method. At the same time, our method is largely determined by the accuracy of the observational data and, in particular, by the random errors in the stellar radial velocities.

Analysis of the identified stars leads us to conclude that, in general, the motion of the centers of mass of the three groups, LCC, UCL, and US, follows the motion characteristic of the Gould Belt; more specifically, they are involved in in its rotation and, in particular, in its expansion. Besides, the entire Scorpius–Centaurus complex has a proper expansion with an angular velocity $k_0 = 46 \pm 8$ km s^{-1} kpc^{-1} at the derived parameters of the kinematic center $l_0 = -40°$ and $R_0 = 110$ pc. Based on this velocity, we estimated the characteristic expansion time of the complex to be $T = 21 \pm 4$ Myr. The proper rotation velocity of the Scorpius–Centaurus complex is lower in magnitude, is determined less reliably, and depends on the data quality and on the parameters of the kinematic center.

Each of the LCC, UCL, and US groups and a number of such young open clusters as β Pic, TWA, Tuc/Hor, and Chamaeleon were probably formed from a single parent cloud of hydrogen.

The structure of the UV-velocity distribution consisting of three roughly parallel branches that we found leads us to conclude that there were three periods of star formation separated by short time intervals in the expanding Scorpius–Centaurus complex.

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