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Kinematics of the Gould Belt Based on Open Clusters

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Abstract—We have redetermined the kinematic parameters of the Gould Belt using currently available data on the motion of nearby young ($\log t < 7.91$) open clusters, OB associations, and moving stellar groups. Our modeling shows that the residual velocities reach their maximum values of -4 km s^{-1} for rotation (in the direction of Galactic rotation) and $+4$ km s^{-1} for expansion at a distance from the kinematic center of ≈300 pc. We have taken the following parameters of the Gould Belt center: $R_0 = 150$ pc and $l_0 = 128°$. The whole structure is shown to move relative to the local standard of rest at a velocity of 10.7 ± 0.7 km s^{-1} in the direction $l = 274° \pm 4°$ and $b = -1° \pm 3°$. Using the derived rotation velocity, we have estimated the virial mass of the Gould Belt to be $1.5 \times 10^6 M_\odot$.

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Key words: *Gould Belt, kinematics, open clusters, Galaxy (Milky Way).*

INTRODUCTION

The Gould Belt is the nearest giant star–gas complex. It has been firmly established that such complexes are regions of active star formation. They are observed not only in our Galaxy (Efremov 1998), but also in other galaxies (Efremov 1989; Efremov and Elmegreen 1998).

The Gould Belt is a member of the older and more massive local system of stars or the Local (Orion) Arm. This belt of bright stars was first identified by Herschel (1847), while the Galactic coordinates of the pole of the great circle of the celestial sphere along which the stars are grouped were determined by Gould (1874). Based on a careful analysis of the spatial distribution and density of OB stars from the Hipparcos catalogue (1997), Torra et al. (2000) improved geometrical parameters of the Gould Belt: the inclination to the Galactic plane, 16°–22°, and the direction of the line of nodes, 275°–295°.

The Gould Belt also includes a system of nearby OB associations (Lindblad et al. 1997; de Zeeuw et al. 1999). In the last decade, more than a hundred T Tauri stars have been found in nearby OB associations and open clusters owing to the spaceborne ROSAT, Chandra, and XMM-Newton X-ray observations, the ground-based 2MASS infrared photometric observations, and the astrometric Hipparcos and Tycho-2 catalogues (Guillout et al. 1998; Mamajek et al. 2002; Wichmann et al. 2003; Makarov 2003). These are late-type low-mass pre-main-sequence stars with ages of several million years that are identified by a number of characteristic signatures—lithium overabundance, X-ray emission, etc. These stars are of interest to us in that they expand the list of stars for studying the kinematics of the Gould Belt.

HI clouds (Olano 1982; Pöppel and Marronetti 2000) and H_2 molecular cloud complexes (Perrot and Grenier 2003) are also associated with the Gould Belt.

The structure of interstellar tenuous hot gas in the immediate solar neighborhood with a radius of 200–300 pc is also closely associated with the Gould Belt. The so-called Local Bubble was found here (Sfeir et al. 1999). In the opinion of Berghöfer and Breitschwerdt (2002), the most realistic theory for the origin of the Local Bubble is the hypothesis about the explosions of ∼20 supernovae in the past 10–20 Myr. Seven neutron stars that are the remnants of these supernovae have already been discovered in the solar neighborhood (Popov et al. 2003).

Several formation scenarios for the Gould Belt have been suggested to date. According to the first scenario, the collision of high-velocity HI clouds with the Galactic disk led to its formation (Franko et al. 1988; Comerón and Torra 1992, 1994). According to the second scenario, a supernova explosion led to the formation of the Gould Belt (Olano 1982; Pöppel and Marronetti 2000). According to the third scenario

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(Olano 2001), the formation of the Gould Belt is a stage in the kinematic evolution of the local system of stars.

Olano (1982) considered a gasdynamic model for the formation of the Gould Belt with a significant initial expansion velocity of the primordial cloud. However, because of the braking of neutral hydrogen caused by the drag of the ambient medium, the expansion velocity dropped to zero. According to this model, it is the zero-velocity boundary that delineates the outer boundary of the Gould Belt (an ellipse with semi-axes of 364 pc and 211 pc was found). The age of the Gould Belt was found using this model to be 30×10^6 yr. The total mass of the expanding hydrogen was estimated to be $1.2 \times 10^6 M_\odot$; the parameters of the system's center were determined: $l_0 = 131°$ and $R_0 = 166$ pc.

Lindblad (2000) suggested a model for the proper rotation of the Gould Belt with an angular velocity, $\omega_0 = -24$ km s^{-1} kpc^{-1}, that coincides in direction with the Galactic rotation, $\omega'_0 = 77$ km s^{-1} kpc^{-2}, as well as the system's expansion with $\rho_0 = 20$ km s^{-1} kpc^{-1} and $\rho'_0 = -117$ km s^{-1} kpc^{-2} for the inferred direction of the rotation/expansion center $l_0 = 127°$ and the adopted $R_0 = 166$ pc. This model takes into account the disk inclination to the Galactic plane, 20°. The model was constructed based on the results of Hipparcos data analysis, which are reflected in the papers by Comerón (1999) and Torra et al. (2000). In contrast to the model by Olano (1982), the model by Lindblad (2000) explains the flat shape of the Gould Belt by the presence of a significant angular momentum.

By modeling the dynamical evolution based on H I and H_2 clouds, Perrot and Grenier (2003) showed that the current main kinematic parameters of the Gould Belt are virtually independent of the direction of initial rotation.

Previously (Bobylev 2004b), we developed Lindblad's approach for the case where the distances are calculated accurately. Using the residual space velocities of individual stars belonging to nearby OB associations, we determined the following kinematic parameters of the Gould Belt: the proper rotation in the direction of Galactic rotation, $\omega_0 = -23.1 \pm 2.2$ km s^{-1} kpc^{-1} and $\omega'_0 = 31.3 \pm 6.5$ km s^{-1} kpc^{-2}, as well as the expansion with $k_0 = 14.0 \pm 2.2$ km s^{-1} kpc^{-1} and $k'_0 = -27.3 \pm 6.5$ km s^{-1} kpc^{-2} for the inferred coordinates of the center $l_0 = 128°$ and $R_0 = 150$ pc.

The Gould Belt is the youngest constituent of the local system of stars. Barkhatova et al. (1989) analyzed the properties of several nearby single open clusters of various ages and some of the open cluster complexes and hypothesized that they belong to a higher-order system, the Supercomplex. The Supercomplex was shown to have a residual rotation with an angular velocity $\omega_0 \approx -12$ km s^{-1} kpc^{-1}.

According to the theory by Olano (2001), the gas out of which the local system of stars was formed had a high initial velocity ($\approx$50 km s^{-1}). The collision of the gas cloud with a spiral density wave led to its fragmentation. In this model, such clusters as the Hyades, Pleiades, Coma, and Sirius are considered as fragments of once a single complex and contraction of the central regions of the parent cloud led to the formation of the Gould Belt.

The Gould Belt is one of the key objects for understanding the evolution of the local system of stars, since its constituents (gas, stars, and clusters) have a low velocity dispersion and have not moved far away from their birthplace. Therefore, improving the kinematic parameters of the Gould Belt is topical.

At present, an unprecedented (in completeness) catalog of 652 open clusters presented by Kharchenko et al. (2005a) and analyzed by Piskunov et al. (2006) has appeared. The goal of this paper is to redetermine kinematic parameters of the Gould Belt based on currently available data on individual clusters. The advantage of this approach over the method with individual stars is that the age and distance estimates for clusters are more reliable.

DATA

We will designate the catalog of 652 open clusters as COCD (Kharchenko 2001; Kharchenko et al. 2005a, 2005b; Piskunov et al. 2006). The young open cluster complex in the solar neighborhood with an age of $\log t < 7.9$ designated by Piskunov et al. (2006) as OCC1 provides a basis for our work list.

In COCD, the random errors of the mean cluster proper motions are small, since the ASCC-2.5 catalog (Kharchenko 2001) compiled from Hipparcos, Tycho-2 (Høg et al. 2000), and several other sources was used to determine them. Data from the catalog by Barbier-Brossat and Figon (2000) served as a basis for deriving the mean radial velocities of the COCD clusters. At present, more accurate stellar radial velocities, the OSACA catalog (Bobylev et al. 2006; Goncharov 2006), are available; their main peculiarity is that they have all been reduced to a single standard. The OSACA catalog combines several major catalogs of stellar radial velocities: WEB (Duflot et al. 1995), Barbier-Brossat and Figon (2000), Nordström et al. (2004), and Famaey et al. (2005), as well as several fragmentary observations taken from $\approx$500 publications.

Young open clusters, which are compact, gravitationally bound systems, are currently believed to be members of larger-scale, but gravitationally less bound, structures, associations. The list of OB associations belonging to the Gould Belt structure and the list of identified Hipparcos stars (probable members of these associations) are presented in de Zeeuw et al. (1999). We compared the two lists of Hipparcos stars, more specifically, the list of OCC1 cluster stars and the list of de Zeeuw et al. (1999). This comparison showed that the Orion complex is fully represented in the OCC1 list of open clusters, while the Scorpius–Centaurus complex is barely reflected in this list. To compile the most complete list of stellar groupings belonging to the Gould Belt structure, we made several additions. These are described in Section 3.1 and are related mainly to the Scorpius–Centaurus complex.

In comparison with our previous paper (Bobylev 2004b), in this paper we made several significant additions for the stars of the Sco–Cen complex using the list of de Zeeuw et al. (1999) and the OSACA database. In our analysis, we included the open cluster Chamaeleontis, the data for which were taken from Sartori et al. (2003), the Hipparcos catalog, and the OSACA database. We used the latest data for 25 TWA cluster stars from Mamajek (2005).

MODELS

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 and the analogous parameter for expansion (Lindblad 2000; Bobylev 2004b). The equations are

$$\begin{aligned} V_r = {} & -u_\odot \cos b \cos l \qquad (1)\\ & - v_\odot \cos b \sin l - w_\odot \sin b + \cos^2 b k_0 r \\ & + (R - R_0)(r \cos b - R_0 \cos (l - l_0)) \cos b k'_0 \\ & - R_0 (R - R_0) \sin (l - l_0) \cos b \omega'_0, \end{aligned}$$

$$\begin{aligned} 4.74 r \mu_l \cos b = {} & u_\odot \sin l - v_\odot \cos l \qquad (2)\\ & - (R - R_0)(R_0 \cos(l - l_0) - r \cos b)\omega'_0 \\ & + r \cos b \omega_0 + R_0(R - R_0) \sin (l - l_0))k'_0, \end{aligned}$$

$$\begin{aligned} 4.74 r \mu_b = {} & u_\odot \cos l \sin b \qquad (3)\\ & + v_\odot \sin l \sin b - w_\odot \cos b - \cos b \sin b k_0 r \\ & - (R - R_0)(r \cos b - R_0 \cos (l - l_0)) \sin b k'_0 \\ & + R_0(R - R_0) \sin (l - l_0) \sin b \omega'_0. \end{aligned}$$

Here, 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, 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, and $u_\odot$, $v_\odot$, and $w_\odot$ are the components of the peculiar solar motion. 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, and the distances R, R_0, and r are in kpc. The quantity ω_0 is the angular velocity 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) contains seven unknowns, $u_\odot$, $v_\odot$, $w_\odot$, ω_0, ω'_0, k_0, and k'_0, to be determined by the least-squares method. The left-hand sides of Eqs. (1)–(3) are assumed to be freed from the differential Galactic rotation.

We also apply a more general method based on the analysis of the linear rather than angular residual velocities, which we approximate by a series of the form

$$V_i = V_{0,i} + a_i(R - R_0) + b_i (R - R_0)^2, \qquad (4)$$

where $i = R, \theta$ and the residual expansion, V_R, and rotation, V_θ, velocities must be obtained by decomposing the observed velocities (components U and V) into the radial and tangential components at fixed parameters of the center, l_0 and R_0. The system of conditional equations (4) contains three sought-for unknowns, $V_{0,i}$, a_i, and b_i, to be determined by the least-squares method.

RESULTS

Improving the Work List of Open Clusters

Using the OSACA catalog of radial velocities, we improved the mean radial velocities for the clusters ASCC 16 and ASCC 18. Two stars, HIP25288 and HIP25302, were used for ASCC 16 in COCD. We suggest adding two more stars, HIP25163 and HIP25235, for which radial velocities are available in OSACA. We calculated the new mean radial velocity of the cluster using three stars (HIP25288 was excluded). The new mean radial velocity for ASCC 16 affected significantly the space velocities U and V, since the difference between the V_r determinations was $\sim$15 km s^{-1}.

Table 1. Space velocities of open clusters and OB associations corrected for the differential Galactic rotation

Cluster	d, pc	U, km s^{-1}	V, km s^{-1}	W, km s^{-1}	n	V_r, km s^{-1}
Makarov	14 ± 4	-9.67 ± 2.04	-21.06 ± 2.22	-6.40 ± 1.81	23	-2.26 ± 2.61
β Pic	31 ± 3	-13.08 ± 1.84	-15.66 ± 2.02	-8.20 ± 1.53	6	7.47 ± 1.93
Tuc/Hor	45 ± 3	-10.25 ± 0.61	-21.60 ± 1.57	-4.91 ± 1.35	8	19.66 ± 1.90
TWA	68 ± 7	-7.62 ± 1.33	-16.59 ± 0.92	-4.25 ± 0.80	22	9.60 ± 0.74
US a	126 ± 2	1.36 ± 0.49	-15.98 ± 1.64	-4.32 ± 0.76	42	1.78 ± 0.33
US b	173 ± 5	2.00 ± 0.55	-19.07 ± 2.05	-4.53 ± 1.02	42	2.45 ± 0.29
UCL a	122 ± 2	-3.15 ± 1.01	-18.62 ± 1.58	-4.10 ± 0.74	66	4.13 ± 0.47
UCL b	170 ± 3	-4.21 ± 1.20	-22.43 ± 1.97	-5.90 ± 1.00	75	4.40 ± 0.40
LCC a	101 ± 1	-7.55 ± 1.32	-16.68 ± 0.83	-6.39 ± 0.72	41	9.06 ± 0.36
LCC b	133 ± 3	-8.07 ± 1.44	-17.91 ± 0.90	-6.74 ± 0.90	58	8.84 ± 0.38
Cham	145 ± 16	-6.95 ± 2.27	-17.22 ± 3.52	-8.35 ± 1.35	9	12.12 ± 4.11
Lac OB1 a	224 ± 15	-1.66 ± 1.42	-8.54 ± 3.99	-1.15 ± 1.54	10	-8.52 ± 4.20
Lac OB1 b	440 ± 20	-3.76 ± 1.51	-12.85 ± 1.20	-3.87 ± 1.51	23	-12.47 ± 1.17
Per OB2	315 ± 23	-20.29 ± 2.29	-5.95 ± 2.03	-7.93 ± 1.63	19	15.94 ± 2.29
Tr 10	375 ± 33	-16.75 ± 1.85	-17.50 ± 3.90	-9.56 ± 1.32	6	20.07 ± 3.92
NGC 2516	380 ± 28	-9.90 ± 1.48	-23.02 ± 0.42	-3.88 ± 0.98	6	22.00 ± 0.31
Col 121	465 ± 28	-12.20 ± 1.81	-11.80 ± 2.17	-7.06 ± 1.37	20	23.22 ± 2.43
Cep OB2	501 ± 36	0.02 ± 1.95	-14.71 ± 2.30	-2.90 ± 1.94	15	-17.07 ± 2.31
ASCC 16	460	-14.22 ± 4.09	-7.96 ± 1.67	-5.39 ± 1.53	3	20.80 ± 4.60
ASCC 18	500	-16.27 ± 10.1	-9.32 ± 4.15	-5.80 ± 3.70	2*	23.8 ± 11.5

Note. n is the number of stars used to calculate the mean radial velocity.

The radial velocity of ASCC 18 in COCD was determined using the star HIP25378. We also suggest adding the star HIP25567.

We suggest attributing the open cluster ASCC 114 to the Gould Belt structure. Unfortunately, only one star was used to calculate the mean radial velocity.

Since the age of the open cluster NGC 2516 is $\log t = 7.91$, it was not included in OCC1 by Piskunov et al. (2006). However, based on the results by Torra et al. (2000) and Bobylev (2004b), we attribute it to the Gould Belt complex.

Piskunov et al. (2006) estimated the probability (P_t) that the clusters Stock 23 and Melotte 20 belong to the Gould Belt structure as 25 and 2%, respectively. We do not include them in the main list to determine the kinematic parameters of the Gould Belt; their membership in the Gould Belt structure is discussed below. The open cluster ASCC 89 has $P_t = 42\%$. However, since this cluster is located fairly far from the presumed kinematic center, in the fourth quadrant ($x = 415$ pc, $y = -250$ pc, it is outside the boundary in Fig. 2), and has a high residual velocity W, we do not consider it either.

Tables 1 and 2 give the space velocities U, V, W calculated for our 49 clusters that were corrected for the differential Galactic rotation. To calculate the velocities U, V, W, which are listed in Table 2, we took all of the input data, more specifically, the coordinates of the centers α, δ, the velocity components $\mu_\alpha \cos\delta$, μ_δ, V_r, their random errors $e_{\mu_\alpha \cos\delta}$, e_{μ_δ}, e_{V_r}, and the mean distances d from COCD without any changes.

We estimated the errors in the velocities U, V, W, which are given in Tables 1 and 2, by assuming that $e_\pi/\pi = 0.1$. The list of stars for Table 1 was compiled under the condition $\pi > 1.5$ mas. The asterisks mark the four clusters for which the random errors e_{V_r} in one of the velocity components U, V, W exceed 5 km s^{-1}. Large errors are almost always, except the Sco–Cen complex, caused by large random errors in the radial velocities. For this reason, we did not use the parameters of the cluster Tr 10 from COCD,

Table 2. Space velocities of open clusters corrected for the differential Galactic rotation

Cluster	d, pc	U, km s^{-1}	V, km s^{-1}	W, km s^{-1}	n
Mamajek 1	105	-11.09 ± 1.65	-18.59 ± 1.14	-10.58 ± 0.63	2
Platais 8	150	-9.07 ± 1.23	-18.86 ± 3.04	-3.68 ± 0.51	5
IC 2602	160	-4.20 ± 1.49	-23.16 ± 2.78	-0.44 ± 0.37	12
IC 2391	176	-23.06 ± 2.34	-15.60 ± 2.51	-6.12 ± 0.64	18
NGC 2451 a	188	-21.47 ± 2.18	-12.78 ± 4.74	-13.38 ± 1.28	8
Col 65	310	-13.59 ± 1.85	-11.10 ± 0.97	-6.85 ± 0.60	9
Col 135	319	-10.13 ± 1.12	-6.90 ± 2.05	-13.86 ± 1.29	4
NGC 2232	325	-7.74 ± 3.71	-8.84 ± 2.58	-9.68 ± 1.10	3
Platais 6	348	-17.28 ± 11.69	-12.88 ± 5.55	-12.53 ± 1.78	2*
ASCC 127	350	-14.12 ± 2.03	-10.43 ± 2.55	-8.42 ± 1.17	2
ASCC 19	350	-12.30 ± 3.45	-8.81 ± 1.66	-6.09 ± 1.38	4
IC 4665	352	-5.98 ± 1.59	-14.39 ± 1.29	-7.50 ± 0.80	17
Stephenson 1	373	-13.29 ± 1.96	-19.50 ± 3.93	-10.20 ± 1.59	2
Col 70	391	-12.05 ± 1.90	-8.89 ± 0.96	-5.81 ± 0.71	21
Alessi 5	398	-12.25 ± 3.34	-20.59 ± 8.38	-7.17 ± 1.24	2*
σ Ori	399	-20.49 ± 0.91	-16.13 ± 1.34	-3.47 ± 1.80	2
NGC 1976	399	-18.35 ± 2.30	-16.00 ± 1.50	-7.11 ± 1.10	24
NGC 1981	400	-19.85 ± 2.06	-11.65 ± 1.34	-6.53 ± 1.14	5
Col 140	402	-11.68 ± 0.87	-13.30 ± 0.85	-14.27 ± 1.33	3
Vel OB2	411	-11.80 ± 1.16	-12.59 ± 3.15	-3.03 ± 0.62	6
Roslund 5	418	-16.33 ± 1.39	-19.04 ± 2.67	-6.93 ± 0.91	11
NGC 2451 b	430	-9.58 ± 2.50	-5.89 ± 6.75	-15.29 ± 2.00	3*
vdB-Hagen 23	437	-13.62 ± 1.19	-10.82 ± 0.67	-5.03 ± 0.78	2
Col 69	438	-25.32 ± 1.37	-11.40 ± 0.94	-7.88 ± 0.96	4
ASCC 20	450	-11.89 ± 4.28	-4.95 ± 1.74	-4.96 ± 1.51	5
NGC 2547	457	-6.98 ± 0.96	-11.05 ± 1.92	-13.82 ± 1.37	9
ASCC 21	500	-13.06 ± 1.28	-7.94 ± 0.81	-5.33 ± 0.71	7
NGC 1977	500	-12.71 ± 2.28	-17.34 ± 2.17	-5.38 ± 1.89	3
NGC 1980	550	-13.54 ± 1.92	-13.22 ± 1.67	-7.07 ± 1.46	5

Note. All of the input data were taken from COCD.

for which the formal error e_{V_r} reaches 15 km s^{-1}. Instead we determined the mean input parameters using the list of stars for Tr 10 that we compiled based on the papers by de Zeeuw et al. (1999), Robichon et al. (1999), and the OSACA catalog.

At present, 13 stars are attributed to the moving cluster β Pic (Ortega et al. 2004). We determined the parameters of the cluster listed in Table 1 using the list of six candidates from Song et al. (2003). These stars form a compact group in the second Galactic quadrant (see Fig. 2).

In our analysis, we included the set of very young and nearby (within 50 pc of the Sun) stars from Makarov (2003, designated as set XY) and Wichmann et al. (2003, designated as set ZAMS) and OSACA radial velocities. These are late-type low-mass pre-main-sequence stars with ages of several million years identified by lithium overabundance and X-ray emission (based on the ROSAT survey).

Depending on the distance, we divided the four associations US, UCL, LCC, and Lac OB1, which contain a fairly large number of stars, in two. The main goal of this formal division is to increase the amount of data for solving Eqs. (1)–(3) and (4). The following distances were used as the boundary ones: 143, 140, 110, and 300 pc for US, UCL, LCC, and Lac OB1, respectively. For the Lac OB1 association, the difference between the mean distances of parts a and b turned out to be largest, ∼220 pc (see Table 1).

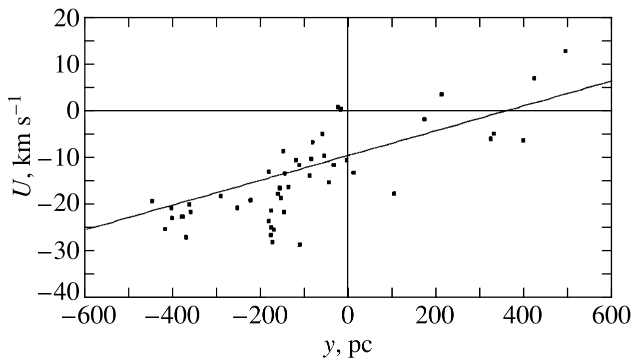

Fig. 1. Dependence of velocity U on coordinate y reflecting the influence of the differential Galactic rotation.

The Motion Relative to the Local Standard of Rest

Based on the linear Ogorodnikov–Milne model, we determined the mean peculiar solar motion using 49 clusters at a mean heliocentric distance of 312 pc, $V_\odot = 19.69 \pm 0.71$ km s^{-1} in the direction $L_\odot = 60° \pm 2°$ and $B_\odot = 21° \pm 2°$. The components of this motion were found to be $(u_\odot, v_\odot, w_\odot) = (9.26, 15.93, 6.96) \pm (0.72, 0.72, 0.60)$ km s^{-1}.

Using these clusters, we determined the mean motion of the Gould Belt complex relative to the local standard of rest, $V_G = 10.7 \pm 0.7$ km s^{-1}, in the direction $L_G = 274° \pm 4°$ and $B_G = -1° \pm 3°$. As the standard solar motion relative to the local standard of rest, we took (10.0, 5.3, 7.2) km s^{-1} from Dehnen and Binney (1998).

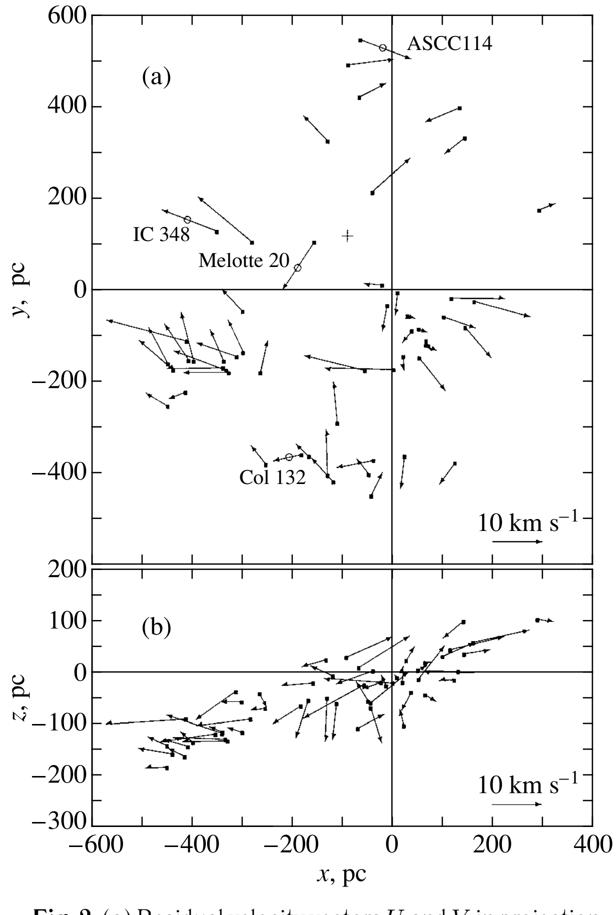

Fig. 2. (a) Residual velocity vectors U and V in projection onto the Galactic xy plane; the circles mark the possible Gould Belt members and the cross marks the kinematic center $l_0 = 128°$ and $R_0 = 150$ pc. (b) Residual velocity vectors U and W in projection onto the Galactic xz plane.

Correction for the Galactic Rotation

Figure 1 shows the dependence of the velocity U of Gould Belt stars on coordinate y: $U = U_0 + Y(dU/dY)$, where $U_0 = -9.3 \pm 0.7$ km s^{-1}. The slope of the line $dU/dY = 26.6$ km s^{-1} kpc^{-1} corresponds to our correction $-(B - A) = -\omega_0$. We use $A = 13.7 \pm 0.6$ km s^{-1} kpc^{-1} and $B = -12.9 \pm 0.4$ km s^{-1} kpc^{-1} found previously (Bobylev 2004a). In the above paper, we determined the following angular velocity parameters for the Galactic rotation by analyzing distant O and B stars: $\omega_0 = -28.0 \pm 0.6$ km s^{-1} kpc^{-1}, $\omega_0' = +4.17 \pm 0.14$ km s^{-1} kpc^{-2}, $\omega_0'' = -0.81 \pm 0.12$ km s^{-1} kpc^{-3} at $R_0 = 7.1$ kpc. Comparison of the two methods of correction for the differential Galactic rotation shows that there are no significant differences between the two methods in the solar neighborhood ≈500 pc in radius under consideration. We then applied a correction for the Galactic rotation by the simpler first method, using the Oort constants A and B.

As can be seen from Fig. 1, there is a local feature in the range -200 pc $< Y < 0$ pc that is related to the proper rotation of the Gould Belt stars. An examination of Fig. 1 shows that the corrections for the Galactic rotation should undoubtedly be applied in the range of distances under consideration.

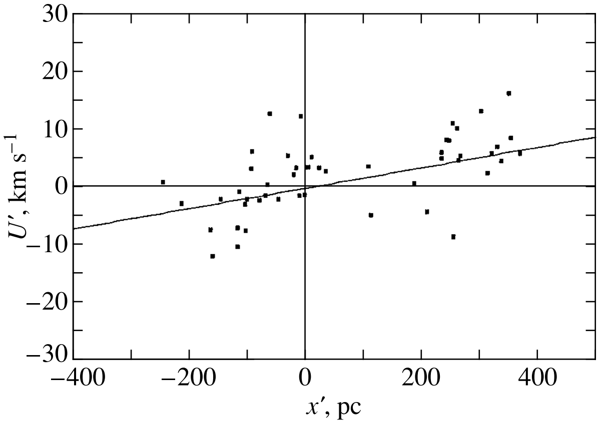

Fig. 3. Residual velocities U' vs. coordinate x' calculated at $l_0 = 160°$.

Residual Rotation and Expansion of the Gould Belt

Figures 2–5 present the residual cluster velocities. The velocities shown in Fig. 4 were freed from the differential Galactic rotation. The velocities shown in Figs. 2, 3, and 5 were freed from both the differential Galactic rotation and the linear motion $(u_\odot, v_\odot, w_\odot) = (9.23, 15.93, 6.96)$ km s^{-1} found above.

Figure 2 shows the residual velocity vectors U and V in projection onto the Galactic xy plane and the residual velocity vectors U and W in projection onto the Galactic xz plane. The circles mark the clusters that we did not use to determine the rotation/expansion parameters for various reasons. The reasons are the following: only one star was used to determine the radial velocity of ASCC 114; there are common stars for calculating the mean radial velocity for IC 348 and Per OB2, the situation for Col 132 and Col 121 being similar; and the open cluster Melotte 20 has a low probability of its membership in the Gould Belt structure.

Figure 3 presents the residual velocities U' as a function of the coordinate x' calculated at $l_0 = 160°$. This figure shows the dependence $dU'/dX' = 17.9$ km s^{-1} kpc^{-1} that corresponds to the first main root of the deformation tensor that was estimated using the linear Ogorodnikov–Milne model from the residual cluster velocities. We see from the figure that, apart from the linear trend, there is a wave with a period of ∼300 pc. We interpret the presence of this wave as the existence of a derivative (in linear velocities) that is related mainly to the expansion effect.

Figure 4 shows the two-dimensional residual velocity UVW distributions for the open cluster complex belonging to the Gould Belt.

Figure 5 presents the residual expansion, V_R, and rotation, V_θ, velocities as a function of the distance from the kinematic center R; the decomposition was performed for $l_0 = 128°$ and $R_0 = 150$ pc. The parameters that we determined by solving the system of Eqs. (1)–(3) are most reliable: $(u_\odot, v_\odot, w_\odot) =$

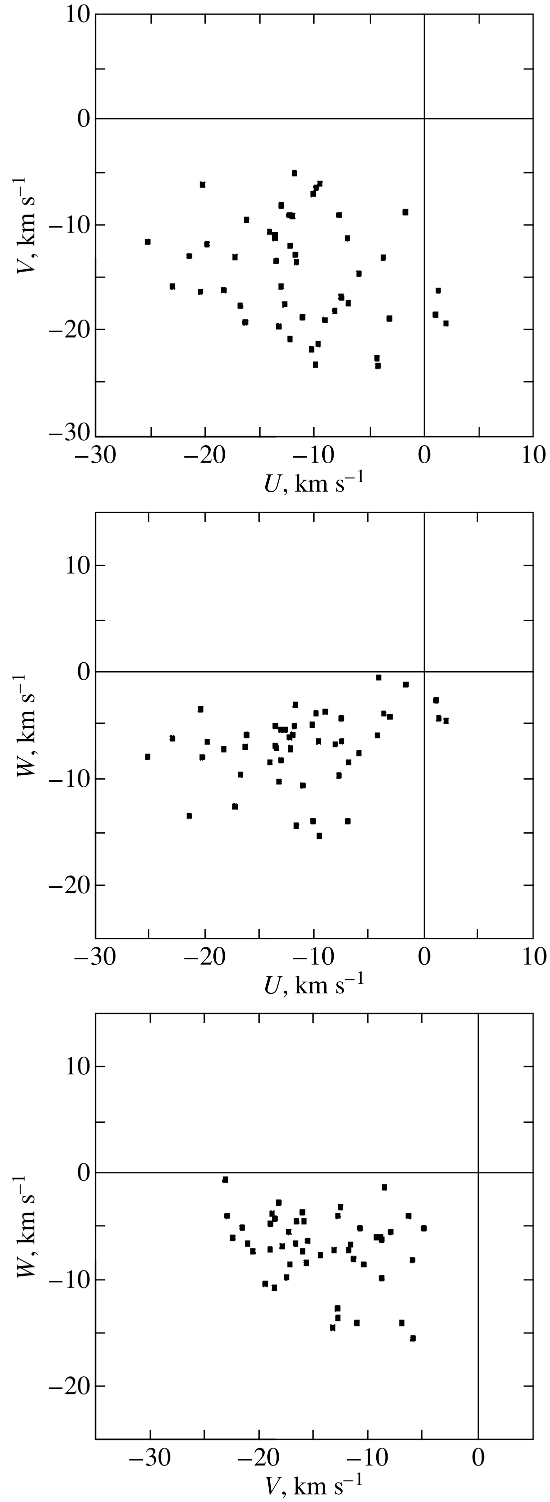

Fig. 4. Two-dimensional residual velocity UVW distributions for the open cluster complex belonging to the Gould Belt.

$(9.6, 17.3, 7.0) \pm (0.9, 0.9, 0.6)$ km s^{-1} and

$$\omega_0 = -18.8 \pm 4.9 \text{ km s}^{-1} \text{ kpc}^{-1}, \quad (5)$$
$$\omega_0' = +32.9 \pm 16.4 \text{ km s}^{-1} \text{ kpc}^{-2},$$
$$k_0 = +22.1 \pm 4.9 \text{ km s}^{-1} \text{ kpc}^{-1},$$
$$k_0' = -58.3 \pm 16.4 \text{ km s}^{-1} \text{ kpc}^{-2}$$

at $l_0 = 128°$ and $R_0 = 150$ pc. We used parameters (5) to construct the rotation and expansion curves in Fig. 5 (curves *1*). For each curve *1* in Fig. 5, the thin lines indicate 1 σ confidence regions.

Figure 5a also presents the expansion curves *2* and *3* whose parameters were found from the linear velocities using Eq. (4). We used all 49 points to determine the parameters of curve *2*: $V_{0R} = 4.1 \pm 2.1$ km s^{-1}, $a_R = -19 \pm 22$ km s^{-1} kpc^{-1}, and $b_R = 8 \pm 49$ km s^{-1} kpc^{-2}. The parameters of curve *3* were determined for the constraint $R < 375$ pc (27 points): $V_{0R} = 4.3 \pm 2.1$ km s^{-1}, $a_R = 49 \pm 40$ km s^{-1} kpc^{-1}, and $b_R = -40 \pm 20$ km s^{-1} kpc^{-2}. In contrast to curves *1* and *3*, curve *2* describes the process where the expansion decelerates immediately. All of the expansion curves found show that the expansion is more local than the rotation.

The parameters of the rotation curve *2* in Fig. 5b were found from the linear velocities using Eq. (4):

$$V_{0\theta} = -1.5 \pm 1.9 \text{ km s}^{-1},$$
$$a_\theta = -23 \pm 20 \text{ km s}^{-1} \text{ kpc}^{-1},$$
$$b_\theta = 40 \pm 45 \text{ km s}^{-1} \text{ kpc}^{-2}.$$

As can be seen from Fig. 5b, there is good agreement between the residual rotation curves for the Gould Belt obtained by the two different methods.

Analysis of the derived curves indicates that the residual velocities are determined reliably only in a close neighborhood, $R \approx R_0$, and are equal to -2.8 ± 0.7 km s^{-1} for rotation and 3.3 ± 0.7 km s^{-1} for expansion. The maximum values are reached by these velocities at slightly different distances ($R_{\max}$) from the kinematic center and are equal to -4.3 ± 1.9 km s^{-1}, $R_{\max} = 360$ pc for rotation and 4.1 ± 1.4 km s^{-1}, $R_{\max} = 265$ pc for expansion. Based on the maximum rotation velocity found, we obtained a virial mass estimate for the Gould Belt, $1.5 \times 10^6 M_\odot$.

We also expanded the list of individual stars that belong to the clusters and associations under consideration. This list contains a total of ~700 Hipparcos star, more that 400 stars of which are members of the Sco–Cen complex. The residual velocities of 658 stars satisfy the criterion $\sqrt{U^2 + V^2 + W^2} < 60$ km s^{-1}. Based on these 658 individual stars, we found the following kinematic parameters of

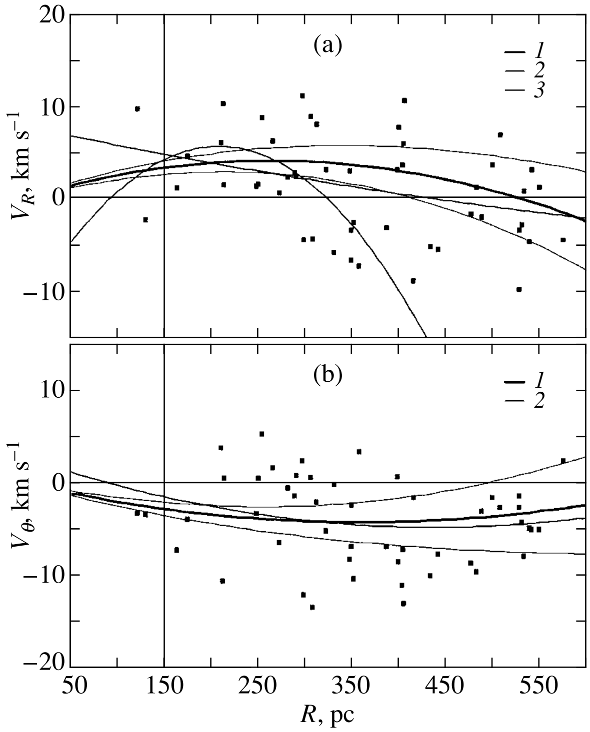

Fig. 5. Residual velocities V_R (a) and V_θ (b) vs. distance from the kinematic center R calculated at $l_0 = 128°$ and $R_0 = 150$ pc; the vertical line marks R_0. See also the text.

the Gould Belt by solving the system of Eqs. (1)–(3): $(u_\odot, v_\odot, w_\odot) = (6.02, 16.71, 5.62) \pm (0.23, 0.23, 0.20)$ km s^{-1} and

$$\omega_0 = -21.4 \pm 1.6 \text{ km s}^{-1} \text{ kpc}^{-1}, \quad (6)$$
$$\omega_0' = +25.7 \pm 5.0 \text{ km s}^{-1} \text{ kpc}^{-2},$$
$$k_0 = +25.6 \pm 1.6 \text{ km s}^{-1} \text{ kpc}^{-1},$$
$$k_0' = -50.5 \pm 5.0 \text{ km s}^{-1} \text{ kpc}^{-2}.$$

The question of whether the expansion of the Gould Belt stars can be related solely to the peculiarities of determining the stellar radial velocities has long been discussed. To test this assumption, we solved the system of only two equations, (2) and (3), (without involving the stellar radial velocities) using the same set of individual stars. The results are the following: $(u_\odot, v_\odot, w_\odot) = (8.42, 15.40, 6.31) \pm (0.27, 0.29, 0.15)$ km s^{-1} and

$$\omega_0 = -20.9 \pm 1.2 \text{ km s}^{-1} \text{ kpc}^{-1}, \quad (7)$$
$$\omega_0' = +33.8 \pm 4.2 \text{ km s}^{-1} \text{ kpc}^{-2},$$
$$k_0 = +28.7 \pm 3.6 \text{ km s}^{-1} \text{ kpc}^{-1},$$
$$k_0' = -50.4 \pm 12.0 \text{ km s}^{-1} \text{ kpc}^{-2}.$$

Comparison of parameters (7) found with parame-

Table 3. Principal semi-axes of the residual velocity ellipsoid $\sigma_{1,2,3}$ and their directions $l_{1,2,3}$ and $b_{1,2,3}$

No.	$\sigma_{1,2,3}$, km s^{-1}	$l_{1,2,3}$, deg	$b_{1,2,3}$, deg
1	$(7.07, 4.30, 3.18) \pm (0.56, 0.51, 0.35)$	153, 241, 130	−14, 5, 75
2	$(5.29, 4.28, 2.75) \pm (0.52, 0.36, 0.42)$	188, 268, 120	−15, 32, 54

ters (6) shows that the expansion is actually a kinematic effect.

The Residual Velocity Ellipsoid

Table 3 gives the principal semi-axes of the residual velocity ellipsoid $\sigma_{1,2,3}$ and their directions $l_{1,2,3}$ and $b_{1,2,3}$. In the first row of Table 3, the parameters were determined from the velocities that were freed from the peculiar solar motion and the differential Galactic rotation. The axial ratios are 8 : 4 : 3.

The second row of this table gives the parameters determined from the cluster velocities that were also freed from the rotation velocity and contraction of the Gould Belt found above (parameters (5)). In this case, the axial ratios are 8 : 6 : 4, i.e., the residual velocity distribution is closer to a spherical one.

There is an appreciable decrease in the residual velocity σ_1. On the whole, we conclude that allowance for the rotation velocities and contraction of the Gould Belt that we found brings the residual velocities $\sigma_{1,2,3}$ closer to the "cosmic dispersion." Since we solved the plane problem (without including the inclination of the Gould Belt to the z axis), the relationship of the residual velocities found (the second row of the table) to the Gould Belt remains noticeable: $b_1 = -15°$ at $l_1 = 188°$; consequently, the true cosmic dispersion must be even lower.

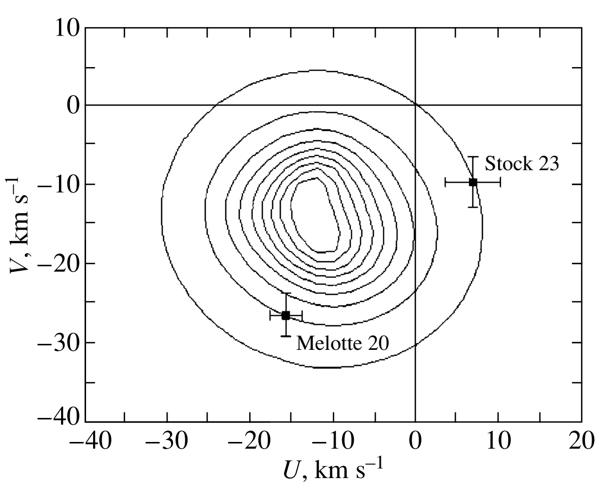

Fig. 6. Smoothed distribution of residual UV velocities.

Probable Members of the Gould Belt Structure

Figure 6 shows the probability density distribution of the residual UV velocities. The residual velocities shown in Fig. 4 serve as the input data for this distribution. We applied an adaptive Gaussian smoothing method where the Gaussian width at each point of the map depends on the density of the data distribution near this point. A detailed description of the algorithm for determining the probability density can be found in Skuljan et al. (1999) and Bobylev et al. (2006). The contour lines in Fig. 6 are given at 10% steps. The positions of two open clusters, Melotte 20 (α Per) and Stock 23, are shown. For all the remaining clusters listed in Tables 1 and 2, the probability exceeds 20%. In particular, this also applies to such clusters as σ Ori, Platais 6, Col 135, Col 140, NGC 2451b, and IC 2602, for which Piskunov et al. (2006) obtained low probabilities P_t (5, 1, 11, 15, 19, and 13%, respectively).

The low probability that we found for Stock 23 may be related to an uncertainty in the radial velocity, since it was calculated using only two stars.

The open cluster Melotte 20 is located at a distance of only 71 pc from the presumed kinematic center. Piskunov et al. (2006) estimated its age to be 35 Myr. The mean radial velocity was calculated using 66 stars. Therefore, this cluster is of considerable interest in studying the kinematics of the Gould Belt and its evolution. However, including it in the data set for determining the rotation and expansion parameters leads to an appreciable increase in the error of a unit weight.

DISCUSSION

The residual rotation velocity of the Gould Belt that we found, $V_\theta = -2.8 \pm 0.7$ km s^{-1} (at $R =$ 150 pc), is in complete agreement with the results of the analysis (based on an independent method) of the motion of OCC1, the youngest open cluster complex, by Piskunov et al. (2006), who found the mean tangential velocity to be $\overline{T}_l = -2.9 \pm 0.7$ km s^{-1}. The discrepancy between the two approaches in estimating the angular velocity ω_G is attributable to the use of different parameters for the kinematic center.

The difference between our residual expansion velocity of the Gould Belt $V_R = 3.3 \pm 0.7$ km s^{-1} (at $R = 150$ pc) and the velocity $V_r = 2.1 \pm 1.1$ km s^{-1} for OCC1 undoubtedly stems from the fact that Piskunov et al. (2006) did not consider the Sco–Cen complex (US, UCL, and LCC), which has the dominant influence on the determination of the expansion effect.

Our estimate of the cosmic dispersion for Gould Belt stars, $(5.29, 4.28, 2.75)$ km s^{-1}, with respect to the first axis is smaller than the estimate by Piskunov et al. (2006), $(7.2, 4.1, 2.6)$ km s^{-1}, obtained for the young open cluster complex with age $\log t = 6.7$. This reduction in the cosmic dispersion can be explained by allowance for the rotation and expansion parameters of the Gould Belt that we found.

Comparison of the parameters derived from mean cluster velocities (solution (5)) and from individual stars (solution (6)) shows that, in the former case, the maximum velocities are found to be a factor of ≈1.5 lower than those in the latter case. This difference is probably related to a difference between the distance scales. We believe the photometric distance estimates obtained by analyzing open clusters (particularly for distant clusters) to be more reliable; therefore, we prefer solution (5).

The kinematic parameters (5) that we found are generally in agreement with the results of Lindblad (2000), Perrot and Grenier (2003), and Bobylev (2004b).

CONCLUSIONS

Thus, we have performed a thorough work on compiling the most complete list of nearby young open clusters, OB associations, and moving stellar groups that belong to the Gould Belt structure. In particular, we showed that the probabilities that the clusters Melotte 20 and Stock 23 belong to the Gould Belt structure are ∼20 and 10%, respectively; the recently discovered (Kharchenko et al. 2005b) open cluster ASCC 114 has a probability of more than 20%. The stellar radial velocity data for such clusters as Platais 6, Alessi 5, NGC 2451b, ASCC 18, ASCC 114, and Stock 23 must be improved. We used the OSACA database to improve the radial velocities for a fairly large number of nearby stars. In particular, we improved the mean radial velocities of the open clusters ASCC 16 and ASCC 18.

The errors in the stellar radial velocities were shown to make the dominant contribution to the errors in the space velocities U, V, W. The nearby clusters of the Sco–Cen complex (US, UCL, and LCC) with a large number of members, where the random errors in the stellar proper motions have the dominant influence, constitute an exception. Thus, the task of improving the stellar radial velocities remains topical; the prospect for its breakthrough accomplishment is related to the accomplishment of the future GAIA space mission.

To determine the kinematic parameters of the Gould Belt, we used data on 45 clusters and OB associations. We took the data for 31 open clusters directly from COCD (Piskunov et al. 2006) and obtained the data for 14 added clusters, moving groups, and associations based on various sources. The mean age of the sample is ≈32 Myr; the clusters are located within ≈500 pc of the Sun. The entire Gould Belt structure was shown to be involved in several motions. First, apart from the involvement in the overall rotation of the Galaxy, the complex as a whole moves relative to the local standard of rest at a velocity of 10.7 ± 0.7 km s^{-1} in the direction $l = 274° \pm 4°$ and $b = -1° \pm 3°$. Second, there is residual rotation and expansion of the system. As the parameters of the kinematic center, we took $l_0 = 128°$ and $R_0 = 150$ pc that we determined previously (Bobylev 2004b). Our modeling showed that the residual velocities are reliably determined in a close neighborhood, $R \approx R_0$, and are equal to -2.8 ± 0.7 km s^{-1} for rotation (in the direction of Galactic rotation) and $+3.3 \pm 0.7$ km s^{-1} for expansion. The maximum values are reached by these velocities at a distance from the kinematic center of ≈300 pc and are -4.3 ± 1.9 km s^{-1} for rotation and $+4.1 \pm 1.4$ km s^{-1} for expansion. Based on the rotation velocity found, we obtained a virial mass estimate for the Gould Belt, $1.5 \times 10^6 M_\odot$.

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