THE GOULD BELT

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Abstract—This review is devoted to studies of the Gould belt and the Local system. Since the Gould belt is the giant stellar-gas complex closest to the sun, its stellar component is characterized, along with the stellar associations and diffuse clusters, cold atomic and molecular gas, high-temperature coronal gas, and dust contained in it. Questions relating to the kinematic features of the Gould belt are discussed and the most interesting scenarios for its origin and evolution are examined.

1 Historical information

Stars of spectral classes O and B that are visible to the naked eye define two large circles in the celestial sphere. One of them passes near the plane of the Milky Way, while the second is slightly inclined to it and is known as the Gould belt. The minimum galactic latitude of the Gould belt is in the region of the constellation Orion, and the maximum, in the region of Scorpio-Centaurus.

Herschel noted [1] that some of the bright stars in the southern sky appear to be part of a separate structure from the Milky Way with an inclination to the galactic equator of about 20°. Commenting on the features of the distribution of stars in the Milky Way, Struve [2] independently noted that the stars that form the largest densifications on the celestial sphere can lie in two planes with a mutual inclination of about 10°.

Gould [3,4] made a detailed study of this structure, determined the galactic coordinates of the pole of a large circle of the celestial sphere along which the stars are in groups, and determined the coordinates of the nodes. He found the inclination of the major plane of stars to 4° with respect to the galactic plane to be 17°. Because of his work, the belt is referred to as the “Gould belt”.

Shapley [5] provided a clear formulation of the fact that, as opposed to the distant spherical clusters which delineate the Galaxy, the close (to 1 kpc) bright stars form a unique separate subsystem of the same type as a local cluster or local system. He proposed that this densification of near, bright B stars be called the Local system.

From a modern standpoint, the term “Local system” is more substantive, since it incorporates not only individual nearby stars of different spectral classes, but also the system of nearby stellar associations and diffuse nebulae, the presence of cold atomic HI, molecular H₂, and high temperature coronal gas and dust.
A number of kinematic features of the bright O and B stars were clarified when the first data on the radial velocities, proper motions, and distances of the stars became available. First, a constant term of magnitude about $+5 \text{ km/s}$ was discovered. This feature was first noticed by Frost and Adams in 1903 and confirmed by Kapteyn and Frost [6] in an analysis of the radial velocities of the “Orion” stars. Following the suggestion of Campbell [7], this term is known as the K-term or the K-effect. The presence of the positive K-term is mostly interpreted as a common expansion of the stellar system [8,9] and only a small fraction of it ($\approx 1.5 \text{ km/s}$) can be explained as a red shift of spectrum lines owing to the gravitation of massive stars in accordance with the theory of relativity. Second, it was shown that the residual velocities of the O and B-stars typically have a small dispersion in their residual velocities of magnitude $\leq 10 \text{ km/s}$, as well as a significant deviation by $20–30^\circ$ of the vertex from the direction to the center of the Galaxy [10,11,12].

The papers of Lindblad [13,14] and Oort [15,16] have had a significant influence on studies of the structure and kinematics of the Galaxy. The existence of interstellar absorption of light was definitively established [17] and many authors contributed to developing models of stellar evolution; O and T associations were discovered [18,19].

This has ultimately led to an understanding that the stars belonging to the Gould belt are not only nearby, but also very young objects (younger than $\approx 60$ million years) that are participating in the differential rotation of the Galaxy, and their galactic orbits are close to circular. It has been shown in a number of papers that the observed residual velocities of the stars in the Gould belt can be interpreted either as a residual rotation of the entire system or as a combination of rotation and expansion.

The early history of research on the Gould belt is reflected in the book by Bok [20]. A systematic discussion of the key questions relating to studies of the Gould belt, along with a detailed bibliography, can be found in the work of Frogel and Stothers [21], Efremov [22], and Pöppel [23].

2 Structure

The Gould belt is the closest giant stellar-gas complex to the sun. Complexes of this sort are regions of active star formation and are not only observed in our Galaxy [24], but also in other galaxies [22,25].

Based on modern estimates, the Gould belt is a quite flat system with semi-axes of $\approx 350 \times 250 \times 50 \text{ pc}$ and is inclined to the galactic plane by $16^\circ–22^\circ$. The ascending node is in the $l_\Omega = 275^\circ–295^\circ$ direction. The sun lies at a distance of about 40 pc from the line of nodes. The center of the system is located at a distance of about 150 pc in the second galactic quadrant. More precise knowledge of the direction to the center depends on the age of the sample, and ranges from $130^\circ$ to $180^\circ$ according to various estimates.

The spatial distribution of the stars is highly nonuniform; a significant drop in their density is observed at a radius of $\approx 80$ pc from the center, i.e., the entire system has a donut shape. The well-known diffuse cluster $\alpha$Per (Melotte 20) with an age of about 35 million years lies near the center of this donut.
2.1 Stellar composition

Pöppel has pointed out [26] that only the relatively near stars no later than spectral class B2.5 can be said reliably to belong to the Gould belt. There are, however, very few of them. In order to assign stars from other spectral classes to the belt, various methods of distinguishing the stars from different populations in the vicinity of the sun are required. In recent decades x-ray data from the ROSAT\textsuperscript{1}, Chandra\textsuperscript{2}, and XMM-Newton\textsuperscript{3} satellites, earthbound infrared photometric data from 2MASS [27], and the HIPPARCOS [28] and Tycho-2 [29] astronomical catalogs have been used.

Torra, et al. [30], have analyzed the extensive HIPPARCOS sample of stars in spectral classes O and B that lie within a radius of $r < 2.0$ kpc of the sun. The individual age of 2864 stars was estimated by Strömgren photometry. The relative error in the age determination for 88% of the stars in the sample was less than 100%. It was concluded that within a radius of $r \leq 0.6$ kpc, about 60% of the stars younger than 60 million years belong to the Gould belt.

Chereul, et al. [31], have estimated the age of 1077 near ($r < 0.125$ kpc) HIPPARCOS stars of spectral classes A and F based on Strömgren photometry. The average error in the age determination was about 30%, but for the youngest fraction it reached 100%. The distribution of AF stars with respect to age has two peaks: the overwhelming majority of the stars are concentrated in the neighborhood of a peak at 650 million years and about 400 stars, in the neighborhood of a peak at 10 million years. We may conclude that 20–30% of the near AF stars may belong to the Gould belt. This estimate agrees with the earlier result of Taylor, et al. [32].

Several hundred T Tau stars have been found in the nearby associations and diffuse nebulae of the Gould belt. These are dwarfs in late spectral classes with masses of $\approx 1M_\odot$ and ages of several million years that have not reached the Main sequence stage. Stars have also been identified in terms of their emission in the HJ line, their lithium abundance, x-ray emission, position in the Hertzsprung-Russell diagram, rapid axial rotation ($v \sin i \approx 30$ km/s an higher), and kinematic characteristics.

X-ray emission in the 0.18–0.3 keV range (ROSAT) makes it possible to detect sources with temperatures below $10^6$ K (approximately later than G0 for Main sequence stars). A significant lithium abundance indicates that an already formed star is in a short-duration state in which thermonuclear reactions have not yet begun. Thus, when there is more lithium, a star is younger. A comparison of the position of these stars on a Hertzsprung-Russell diagram with appropriate isochrones makes it possible to select the youngest objects. A relationship between the lithium abundance, age, and kinematics of the closest young dwarfs has been demonstrated by Wichman, et al. [33].

Figure 1 is an illustrative sample of candidate T Tau stars from the Scorpio-Centaurus association based on data from Ref. [34]. In the left frame the candidates are indicated by open circles and crosses, and in the right, by solid circles.

The T Tau stars are divided into several categories: classical (CTTS, classical T Tauri stars) are the youngest objects with ages less than 10 million years and they still have

\textsuperscript{1}ROentgen SATellite, operated from 1990-1999.
\textsuperscript{2}X-ray telescope, operating in orbit since 1998.
\textsuperscript{3}X-ray telescope, operating in orbit since 1999.
a dust disk; stars with less marked characteristics (WTTS, weak-line T Tauri stars) are older and lie closer to the Main sequence; and the oldest stars of this type (PTTS, post-T Tauri stars).

There is also some interest in the very young massive star-formation regions with an emission spectrum–Herbig–Haro objects (a wide class of stars designated as HAeBe) which are also in a stage of not having reached the Main sequence. About ten of these have been discovered among the nearby OB associations related to the Gould belt [35].

We note that about 40 unidentified γ-ray sources with energies above 100 MeV have been detected (using the EGRET system on board CGRO\textsuperscript{4}). Their distribution has a statistical relation to the Gould belt, but the nature of these sources is still not clear.

2.1.1 Moving groups and diffuse stellar clusters

Diffuse stellar clusters lie within a wide region near the sun. Their distances and ages have been estimated reliably, so they are of great interest for studying the kinematics of the Galaxy, in particular of the Gould belt. The HIPPARCOS and Tycho-2 catalogs have made it possible to determine the average values of the proper motions of the diffuse stellar clusters with fair accuracy. These data, together with the radial velocities, can be used in a three-dimensional kinematic analysis.

The COCD catalog [36], which is complete out to \( r \approx 0.8 \) kpc, is of interest. This catalog has been used to separate diffuse stellar clusters belonging to the Gould belt from the common background. Diffuse stellar clusters with ages below 80 million years were used. This ultimately yielded a sample of 23 diffuse stellar clusters lying within a radius of \( r < 0.5 \) kpc, for which the probability of their belonging to the Gould belt was estimated to be \( P_t = 68\% \). \( P_t \) was determined from the kinematics of the diffuse stellar clusters.

\[^4\text{Compton Gamma-ray Observatory, a satellite that operated during 1991–2000.}\]
There are definite signs that the recently discovered near and very young diffuse stellar clusters and moving groups β Pic, TWA, Tuc/Hor, η Cha, and ε Cha also belong to the Gould belt as members of the Scorpio-Centaurus association or of its diffuse corona. Assuming that the stars in a diffuse stellar cluster were formed simultaneously, it is possible to determine the age of the diffuse stellar cluster by comparing the position of the stars on a Hertzsprung-Russell diagram with suitable isochrones.

It has been shown [37,38] that the well-known group parallax method can be used to determine the individual distances of stars in nearby (no more than 150 pc from the sun) diffuse stellar clusters, such as the Hyades, more accurately than from the HIPPARCOS parallaxes. This, in turn, makes it possible to “improve” the Hertzsprung-Russell diagram. According to modern concepts, as compact gravitationally coupled systems, young diffuse stellar clusters form part of structures of a larger spatial scale, i.e., associations.

### 2.1.2 Stellar associations

With the appearance of the first data on the spectral classes of bright stars, many researchers isolated certain distinct groups of stars in classes O and B. Later, Ambartsumyan [18] suggested that these should be called associations.

The hypothesis of a low spatial density and, thereby, the dynamic instability of associations in the tidal force field of the Galaxy was also first advanced by Ambartsumyan [19]. He estimated that an association should disperse over no more than $10^8$ – $10^9$ years. Blaauw showed [39] that the differential rotation of the Galaxy causes an association with an initially spherical shape to stretch out into an ellipse with a time-varying orientation.

The Scorpio-Centaurus association is the closest to the sun. Blaauw made [40] the first estimate of the kinematic age of this association, ≈20 million years, by analyzing the radial velocities of the stars using the expansion coefficient $K = 50$ km/s/kpc which he found. This age corresponds to the time over which the star covers the characteristic radius of the region occupied by the association. A critical review of models for the formation of the Scorpio-Centaurus association has been written by Sartori, et al. [41]. Associations are young systems with ongoing star formation. The closest associations are of undoubted interest for studying the Gould belt.

A detailed description of the known OB associations within a radius of ≈1.5 kpc, including ones belonging to the structure of the Gould belt, by Zeeuw, et al. [42], makes use of the probable members among selected HIPPARCOS stars. This list included the following associations: Cep OB2, Lac OB1, Cep OB6, Per OB2, Cas-Tau, Sco-Cen (US, UCL, LCC), Tr 10, Vel OB2, and Col 121. A description of and the stellar composition of the association Ori OB1 can be found in the paper by Brown, et al. [43]. The distribution of these associations in the galactic plane is shown in Fig. 2.

It has been shown [45,22] that the OB associations and young clusters (B2 and younger) within 3 kpc of the sun may be combined into complexes with sizes of 150–700 kpc. Almost all of them contain giant molecular clouds with masses $\geq 10^5 M_\odot$. Many of the complexes are coupled to giant clouds of neutral hydrogen. The Gould belt is one of these giant complexes.
2.1.3 The Local system of stars, Supercluster, Supercomplex

According to Mineur [46,47], besides participating in the common galactic rotation, the Local system of stars gives signs of rotating around a center that does not coincide with the center of the Galaxy. This idea was examined with more extensive data by Shatsova [48]. She found an intrinsic rotation of the Local system that was in the same direction as the galactic rotation. Here the Local system was treated as the set of all nearby stars. The problem of separating the \( \approx 33000 \) stars of mixed spectral composition in the Boss catalog into fractions (according to signs of participation in the galactic rotation) was not addressed. Thus, as noted by Shatsova, her results were of a preliminary nature. The size of the region of space being analyzed and specified by the Boss catalog was estimated to be 300–350 kpc. The kinematics and dynamics of the Local system occupy a special place in the book by Ogorodnikov [9].

Tsvetkov [49,50,51] undertook further study of the Local stellar system of stars based on Shatsova’s equations. He showed, first of all, that the systematic errors in the GC, N30, FK4, and FK5 catalogs did not lead to significant differences in the parameters of the Local system. Second, with data from the HIPPARCOS catalog he obtained solutions separately for groups of stars subdivided according to spectral class and to distance from the sun. Ultimately, it was possible to localize the Local system on a Hertzsprung-Russell diagram as a system of stars of spectral classes A-F in the Main sequence, formed near the center, and lying in the \( l = 253^\circ \div 9^\circ, b = -13^\circ \div 9^\circ \) direction at a distance of 180 pc from the sun. The rotation is counter-clockwise, i.e., in a direction opposite to the galactic rotation, with a period of about 140 million years in a plane inclined to the plane of the
galaxy by 30°X. The Local stellar system has no effect on the motion of stars at distances greater than 300 pc from the sun. 

The idea of the Supercluster was developed by Eggen [52,53], who combines several fairly young clusters into the Pleiades group (age 100–150 million years) based on the closeness of their kinematics and names this group the “Local association”. The spatial velocities of the stars (calculation of which required high precision parallaxes) were used to select the members of the association. One gets a sense that the group was not selected entirely correctly. In fact, in those years high precision trigonometric parallaxes existed only for a very small (≈50 pc) neighborhood of the sun, so only the nearest stars were used. Eggen’s lists of the members of the Pleiades group (the current name for the Local association) are used, for example, in Refs. 54 and 55.

Barkhatova, et al. [56], analyzed the properties of a number of isolated diffuse stellar clusters of different ages near the sun and advanced the hypothesis that they belong to a higher order system, the Supercomplex. The diameter of the Supercomplex was 2000 pc, its thickness was 150 pc, and 11 complexes of diffuse stellar clusters and 4 isolated diffuse stellar clusters were assigned to it. It was shown that the Supercomplex has a residual rotation with an angular velocity of ≈12 km/s/kpc in the same direction as the galactic rotation. The Supercomplex has a size comparable to the Orion arm. The idea that the Gould belt is part of the Orion arm was discussed some time ago, but its most complete expression is to be found in the dynamic model of Olano [44], which will be discussed in more detail in section 3.3.

2.2 Interstellar medium

2.2.1 Neutral hydrogen HI

An analysis of the earliest observations of neutral hydrogen at 21 cm showed that its distribution is related to the Gould belt [57,58].

Lindblad, et al. [59,60] have shown that the motion of nearby hydrogen clouds has the same kinematic features as for the Gould belt — a common expansion effect. This has been confirmed by others. Lindblad isolated and studied a region which he referred to as “detail A,” which is still known as the Lindblad ring. The spatial dimensions of the ring are ≈ 800 × 500 pc [61] and its center lies in the second galactic quadrant, close to the presumed center of the Gould belt. This implies that the Gould belt is surrounded by a giant cloud of neutral hydrogen.

2.2.2 H2 molecular clouds and HII zones

Direct study of the distribution of molecular hydrogen in the Galaxy is difficult because it has no emission lines in the radio range. There is a reliable indirect method based on the relative content of carbon monoxide CO and molecular H2, which equals 6 × 10^{-5}. Thus, the 2.6 mm CO radio line turned out to be a convenient indicator of the distribution of molecular hydrogen. A detailed discussion of the methods for observing the CO line and a catalog of molecular clouds can be found in a paper by Dame, et al. [62].

The relation between the Gould belt and low-latitude (|b| ≤ 24°) molecular clouds and their distributions and kinematics have been studied by Taylor, et al. [32], who show that
The motion of the clouds is consistent with a model of expansion of the Gould belt. An analysis of the distribution over the celestial sphere of high-latitude (|b| ≥ 25°) molecular clouds [63] shows that they form two extended shells associated with the two closest OB associations in the Gould belt: Per OB3/Cas-Tau and Sco-Cen.

There is a very close relationship between molecular clouds and star-formation regions in the Galaxy. This is because stars are formed inside these clouds. Zones of ionized hydrogen develop around very young and massive O or B stars and these are indicators of star-formation regions. One of the best known HII zones, the Orion nebula (the association Ori OB1), lies in the Gould belt.

A paper by Porras, et al. [64], provides the most complete discussion of observational data in the near infrared (J,H,K) of the youngest stellar groups (with ages of a few million years) within a radius of 1 kpc from the sun and demonstrates their close relationship to the distribution of molecular clouds. That distribution, constructed on the basis of about 7200 stars, is shown in Fig. 3, where the sizes of the circles correspond to three categories of groups depending on the number of stars, n < 30, 30 < n < 100, and n > 100, respectively. Complexes of molecular gases lying within a circle of 0.5 kpc, Ori, Per OB2, Tau, Cha, Oph, as well as a number of smaller objects, belong to the Gould belt.

During their formation, protostars have extended shells within which maser emission is produced. Their trigonometric parallaxes and proper motions have been determined by very-long base-line radio interferometry (VLBI) to a very high accuracy, averaging 5–10%.

Methanol (CH$_3$OH, 6.7 GHz, 12.2 GHz) and water (H$_2$O, 22.2 GHz) masers have
Figure 4 shows the distribution of the masers with measured trigonometric parallaxes in an extensive neighborhood of the sun within a radius of about 4 kpc. The local arm (the Orion arm), which traces massive (solid circles) and low-mass protostars (open circles) can be seen clearly.

### 2.2.3 Coronal gas

An interstellar rarefied hot gas structure with a temperature of $\approx 10^6$ K and a radius of 200–300 pc in the immediate vicinity of the sun is closely coupled to the Gould belt. It includes such regions as the “Local bubble” and North polar spur (or Loop I superbubble).
Рис. 5: Spatial distribution of the regions of coronal gas according to Heiles [82]. The circle with the sun in the center indicates the Local bubble.

The local bubble is a compact region that is essentially free of absorbing material, so it was first discovered in an analysis of interstellar stellar reddening by Fitzgerald [73]. Charts of the distribution of neutral gas absorption in NaI lines, constructed by Sfeir, et al. [74], indicate an inclination to the Galactic plane, as for the Gould belt.

The physical processes leading to the appearance of bubbles are generally as follows. In young diffuse stellar clusters there are many supernova explosions. This leads to the appearance of stellar winds and the formation of shock waves which sweep gas to the periphery of a given local region, where it creates densifications in the form of shells or extended walls. At the boundary of a shell the gas density increases substantially, the gas cools, and molecular clouds form. If a bubble is subject to irradiation from a supernova, the gas in the bubble will be heated and emit x-rays.

Clumps of gas-dust protostellar matter, from which stars will later be formed, develop in cold fragments of molecular clouds. A model for subsequent star formation in molecular clouds connected with OB associations is described by Preibish and Zinnecker [75] with the Scorpio-Centaurus association as an example.

Berghofer and Breitschwerdt [76] believe that the most realistic theory for the origin of the Local bubble involves a repeated, not simultaneous but spread out in time, explosion of about 20 supernovae over the last 10–20 million years. At present, 7 neutron stars are observed in the region of the Gould belt [77,78] and they could definitely be the residues of such supernovae.

The lifetime of bubbles or caverns are not very long compared to the age of the Gould belt; this supports the view [79–81] that the formation of the Local bubble and the
North polar loop are most likely caused by supernova explosions in the Scorpio-Centaurus association.

Regions of rarefied hot gas of this sort are known within a radius of about 0.8 kpc of the sun: a nebula in Vela (Gum Nebula), a complex in Orion-Eridan (associated with the Barnard loop), and the giant supershell GSH 238+00+09 (NSB new star bubble) recently identified by Heiles [82]. Their spatial distribution is illustrated in Fig. 5 where the center of the Lindblad ring, the OB association Col 121 and Per OB2, and the star formation region in Monoceros (Mon R2) are indicated (and the Olano model is plotted). Two contours are shown for the supershell NSB: the smooth curve indicates a $550 \times 217$ pc ellipse at $b = 0^\circ$ and the dashed curve, a $605 \times 480$ pc ellipse at $b = -30^\circ$. As Heiles has pointed out, because of errors in the distance determinations the actual boundaries of the supershell may be entirely different, especially as regards its extended profile indicated by the smooth curve in the figure. The origin of the supershell GSH 238+00+09 is still unclear.

A large-scale rarefied hot gas structure called the Great Rift is known to exist near the sun. Dense clouds of gas and dust lie along the boundaries of the Great Rift.

2.2.4 Dust

The total mass of interstellar dust in the vicinity of the sun is about 1% of the overall mass of available hydrogen [57,58]. Dark dust clouds are a serious problem when estimating the photometric distances to stars or diffuse stellar clusters. A number of authors have suggested that the Local system is purely virtual and shows up because of nonuniformities in the distribution of absorbing material [36].

Observations of dust concentrated in the disks surrounding individual young stars are currently of great interest for recovering the history of star-formation. The JCMT (James Clerk Maxwell Telescope) project is aimed at solving this problem; it is to make submillimeter wavelength observations of star-formation regions belonging to the Gould belt during 2007–2009 [83]. Frisch [84] has written a detailed review of the properties of the interstellar medium in the vicinity of the sun.

2.3 Kinematics

Here we note some results obtained before and after the HIPPARCOS experiment. Based on a linear Ogorodnikov-Milne model, Westin [85] has analyzed $\approx1500$ stars in spectral classes O-A0 in the sun's vicinity, as well as another 500 bright stars. The age of the individual stars was estimated using 4 color and $H\beta$ Strömgren photometry. The available radial velocities, as well as the proper motions of the stars from the FK4 catalog, were invoked. The criterion for belonging to the Gould belt was an age limit for the stars of $\tau < 30$ million years.

Lindblad, et al. [86], have made a similar analysis using $\approx2440$ HIPPARCOS OB stars, for which Strömgren photometry data are available. Besides the $\tau < 30$ million years criterion, stars lying inside the Lindblad ring were considered to belong to the Gould belt.

Comeron [87] has used an epicycle approximation method for analyzing the motions
Based on a linear Ogorodnikov-Milne model, Torra, et al. [30], have made an extensive analysis of \( \approx2500 \) HIPPARCOS OB stars drawing on the available data on the radial velocities of the stars. It was shown that the Oort parameter depends significantly on the age of the stars and the K-effect was carefully studied. For OB stars younger than 60 million years, the expansion velocity reaches \( 7.1 \pm 1.4 \) km/s/kpc for an average sample radius of 100 pc; at larger distances from the sun this velocity becomes negative with large measurement errors. A special experiment showed that the expansion effect remains even if the stars in the Scorpio-Centaurus and Ori OB1 associations are excluded. This is interesting because OB associations have their own noticeable intrinsic expansion; the kinematic method for estimating their age is based on this expansion [40].

Table 1 lists the parameters of the linear Ogorodnikov-Milne model and the Oort constants \( A, B, C, \) and \( K \) [85,86,30] for members (upper part of the table) and non-members (middle of the table) of the Gould belt. Nearby stars in a neighborhood with a radius of \( \approx600 \) pc were considered. In the lowest section of the table the Oort constants \( A, B, C, \) and \( K \) characterize the differential rotation of the Galaxy. The second column gives the number of stars, \( n_\star \). It can be seen from the table that the data from various authors show consistently that the Oort parameters for the stars in the Gould belt differ significantly from the parameters for the galactic rotation.

Based on a sample of 49 nearby diffuse stellar clusters with an average age of 32 million years, Bobylev [88] has shown that the Gould belt participates in several motions. First, besides involvement in the common rotation of the Galaxy, the entire complex as a whole moves relative to the local standard of rest at a velocity of \( 10.7 \pm 0.7 \) km/s in the \( l = 274^\circ \pm 4^\circ, b = -1^\circ \pm 3^\circ \) direction. Second, there is a residual rotation and expansion of the system. The parameters of the kinematic center were taken to be \( l_0 = 128^\circ \) and \( R_0 = 150 \) pc. The residual velocities reach a maximum of \( -4.3 \pm 1.9 \) km/s for the rotation and \( 4.1 \pm 1.4 \) km/s for the expansion with a distance from the kinematic center of \( \approx300 \) pc.

We note that accounting for the influence of the rotation of the Galaxy plays an important role in analyzing the kinematics of the Gould belt. However, the parameters of the spiral pattern, such as the number of arms, twist angle, rotational velocity of the

| Age, million years | \( n_\star \) | \( A \) km/s/kpc | \( B \) km/s/kpc | \( C \) km/s/kpc | \( K \) km/s/kpc | Source |
|-------------------|----------|----------------|----------------|----------------|----------------|--------|
| \(< 30\)          | 275      | \(-8.5 \pm 2.7\) | \(-24.5 \pm 2.7\) | \(10.5 \pm 2.7\) | \(7.4 \pm 2.7\) | [85]   |
| \(< 30\)          | 144      | \(-6.1 \pm 4.1\) | \(-20.6 \pm 5.2\) | \(2.9 \pm 3.7\)  | \(11.0 \pm 3.5\) | [86]   |
| \(< 30\)          | 361      | \(5.7 \pm 1.4\)  | \(-20.7 \pm 1.4\) | \(5.2 \pm 1.4\)  | \(7.1 \pm 1.4\)  | [30]   |
| \(> 60\) not members | 445      | \(15.1 \pm 3.6\) | \(-11.8 \pm 3.6\) | \(-9.2 \pm 3.6\) | \(-2.5 \pm 3.6\) | [86]   |
| \(> 60\)         | 291      | \(13.7 \pm 1.0\) | \(-13.6 \pm 0.8\) | \(0.8 \pm 1.1\)  | \(-1.1 \pm 0.8\) | [86]   |
| \(0.6-2\) kpc    | 932      | \(11.8 \pm 1.5\) | \(-11.0 \pm 1.4\) | \(-0.9 \pm 1.5\) | \(-3.5 \pm 1.7\) | [30]   |
|                   | 449      | \(13.0 \pm 0.7\) | \(-12.1 \pm 0.7\) | \(0.5 \pm 0.8\)  | \(-2.9 \pm 0.6\) | [30]   |
pattern, and phase of the sun in the spiral wave are poorly known. Bobylev and Bajkova have studied [89] a sample of 220 stars, some of which were mostly distant stars of spectral classes O-B2.5 while the others (belonging to the Gould belt) were massive HIPPARCOS B-stars with parallax errors of no more than 10%. Figure 6 shows the galactocentric radial velocities of these stars as functions of their galactocentric distance $R$. A wave with a length of about 3 kpc and an azimuth of about 10 km/s shows up clearly. It is related to the influence of a galactic spiral density wave in the velocities of the stars. It was shown that the perturbation in the radial velocities has a similar phase for both distant and nearby stars. A line corresponding to a velocity gradient of $dV_R/dR = 40$ km/s/kpc is drawn in the figure. This gradient is part of the classical kinematic K-effect, which we mentioned at the very beginning of this article: $K = 0.5 \left[ \frac{\partial V_R}{\partial R} + \frac{1}{R} \frac{\partial V_\theta}{\partial \theta} + \frac{V_R}{R} \right]$. This straight line shows that the “observed” expansion of the Local system of stars (the Gould belt, in particular) is essentially a manifestation of a local perturbation caused by the spiral density wave. The parameters of the velocity of the perturbation from the spiral wave in the residual rotation velocities of the stars are different for the nearby (Gould belt) and distant stars. This is especially noticeable from the phase of the sun in the spiral wave. This indicates that the Gould belt may have an intrinsic residual rotation that is unrelated to the influence of the spiral density wave.

### 2.4 Age

Various methods have been used to estimate the age of the Gould belt. Frogel and Stothers [21] have written an interesting review of these methods. Here we supplement their approach by adding some current results.

Estimates of the age of the Gould belt based on the measured expansion coefficient
for stars and for gas clouds \([21,60,85,87,90–94]\) yield values in the range of 30–70 million years. (A wider range of 30–220 million years is given in the above review \([21]\).)

Estimates of the age of the Gould belt based on the motion of the vertex \([9]\) lie in the range of 20–70 million years. Estimates of the age of individual stars in the Gould belt using, for example, Strömgren photometry \([30]\), show that stars with ages <90 million years belong to this structure. The ages of diffuse stellar clusters and OB associations have been estimated by comparison with isochrones which show that the diffuse stellar clusters with ages <80 million years belong to the Gould belt \([36]\); the average ages of the individual OB associations do not exceed 50 million years \([42]\).

All of the above results are in good agreement among themselves. At present, it is usually assumed that the average age of the Gould belt is \(\approx 60\) million years.

A number of authors have found an intrinsic rotation of the Gould belt \([48,95,61,94,88]\). Estimates of the age of the Gould belt obtained using the angular velocity of its rotation yield values in the range of 50-500 million years and differ most strongly from the estimates based on the other methods. We note that a value of \(\approx 80\) million years, close to the lowest value in this range, based on the angular rotation velocity of the Local system, \(-1.63"/(100\text{ yr}) = -77\text{ km/s/kpc}\), was obtained by Shatsova \([48]\). An analysis of modern data does not confirm such a large value for this quantity. Modern determinations of the intrinsic angular rotation velocity of the Gould belt give a value between \(-25\) and \(-20\text{ km/s/kpc}\) \([61,88]\) and in this case the estimated rotation period is 200÷300 million years. This paradox has not yet been resolved.

### 2.5 Mass

Table 2 lists the estimated mass of the Gould belt and its individual components obtained by various authors based on different data and methods.

Original estimates of the mass of neutral hydrogen and dust were obtained by Davis \([58]\) using their concentration as derived from an extensive program of observations of radio-frequency hydrogen lines. They obtained a preliminary estimate for the mass of all the stars in the different spectral classes belonging to the Gould belt.

Lindblad estimated \([59]\) the mass of neutral hydrogen on the basis of an analysis of original 21 cm radio observations. The estimate of the mass of neutral hydrogen in the paper by Olano \([96]\) was based on assuming a supernova explosion, followed by expansion and slowing down of the resulting shell. The mass of the Gould belt has been estimated by others \([32,12,93]\) beginning with similar assumptions. They have pointed out that the difference between these estimates and that of Olano \([96]\) mainly arises from the use of different values for the density of stars in the vicinity of the sun.

To estimate the overall mass of molecular H\(_2\) clouds belonging to the Gould belt, Taylor, et al. \([32]\), have reanalyzed the data of Lynds \([97]\) taking into account the redistribution of matter that is typical of the Gould belt. The total mass of the stars in the Gould belt was estimated quite carefully, using an initial mass function derived from the data of various authors.

Lindblad \([61]\) and Bobylev \([88]\) have made virial estimates—Lindblad by analyzing the kinematics of the youngest fraction of the HIPPARCOS OB stars and Bobylev by analyzing the rotation curve for 49 diffuse stellar clusters and associations belonging to the
Table 2: Estimates of the Mass of the Gould Belt and its Individual Components

| Component     | Age, million years | Radius, pc | Mass, $M_\odot$ | Source |
|---------------|-------------------|------------|----------------|--------|
| Stars         | —                 | ≈ 500      | $10^4 - 10^5$  | [58]   |
|               | 45 – 90           | 500        | $5 \times 10^5$ | [32]   |
| HI            | —                 | ≈ 500      | $2.6 \times 10^4$ | [58]   |
|               | 60                | ≈ 600      | $1 \times 10^6$  | [59]   |
|               | 30                | ≈ 300      | $1.2 \times 10^6$ | [96]   |
|               | 16                | ≈ 300      | $3.3 \times 10^5$ | [12]   |
|               | 26                | ≈ 300      | $2.4 \times 10^5$ | [93]   |
| $H_2$         | ≤ 60              | ≈ 300      | $4 \times 10^5$  | [32]   |
| Dust          | —                 | ≈ 500      | $6 \times 10^4$  | [58]   |
| Mass in center| 20 – 40           | < 500      | $1 \times 10^6$  | [61]   |
|               | 32                | < 500      | $1.5 \times 10^6$ | [88]   |

Gould belt. This approach is based on the assumption that all of the mass is concentrated in the center, while the motion of the stars obeys the Kepler law. This method yields an estimate for all the gravitational mass within a specified volume of space.

Table 2 shows that the major contribution to the mass of the Gould belt is from neutral hydrogen. Thus, the Gould belt is properly referred to as a gas-stellar complex.

3 Formation scenarios

A number of scenarios have been proposed for the formation of the Gould belt. According to one, it was formed as the result of a supernova explosion. According to a second scenario, it was formed as the result of the collision of high-velocity clouds of neutral hydrogen with the Galactic disk. According to a third, the formation of the Gould belt is a stage in the kinematic evolution of the Orion arm.

As noted by Pöppel [26], on the whole the star-formation process in the sun’s surroundings could have been provoked by the passage of the Carina-Sagittarius arm through this region. A process of spontaneous star formation and its propagation could also have played a role.

3.1 Supernova explosion

This approach is based on Blaauw’s proposal [98] that the Gould belt could have formed as the result of the expansion of extremely hot gas from a very small spatial volume, i.e., an explosion. An explosion of this sort would produce an expanding shell. As a source of stellar wind or an explosion, Blaauw [99,100] examined the stars in the Cas-Tau OB association. At present, this association is spread out over a substantial space, but the cluster a Per lies at its center (Fig. 2). As a whole, the distribution of the nearest OB associations belonging to the Gould belt [100] does not entirely match the predictions of
this model, so that Blaauw [100] concludes that the model is not complete.

Nevertheless, based on the model of a supernova expression, a number of important results have been obtained by Olano [96], Moreno, et al. [12], Pöppel and Marronetti [101], and Perrot and Grenier [93].

Olano [96] examined a gas dynamic model for the formation of the Gould belt with a substantial initial expansion velocity ($\approx 20$ km/s) of an initial hydrogen cloud. Because the gas slows down owing to the drag of the surrounding medium, the zero velocity limit outlines the outer boundary of the Gould belt. An ellipse with $\approx 20$ pc semiaxes centered at $l_0 = 131^\circ$ and $R_0 = 166$ pc was found (Fig. 2). The other parameters found in Olano’s paper have already been mentioned above.

Lindblad [61] has proposed a model of intrinsic differential rotation and expansion of the Gould belt which was considered as a gravitationally-coupled system with an angular velocity of $\omega_0 = -24$ km/s/kpc coincident with the direction of the galactic rotation along with expansion of the system with an angular velocity coefficient $\rho_0 = 20$ km/s/kpc for the found center parameters $l_0 = 127^\circ$ and $R_0 = 166$ pc. This model takes into account an inclination of the disk to the galactic plane of $20^\circ$ and was constructed using results from an analysis of the HIPPARCOS OB stars obtained in Refs. 102 and 87. As opposed to the Olano model [96], the Lindblad model [61] explains the flat shape of the Gould belt in terms of its having a substantial angular momentum. Bobylev [94,88] extended the Lindblad approach to the nonlinear case with an exact calculation of the distance from the kinematic center of the system to stars (using the measured parallaxes of the stars); similar values of the kinematic parameters were obtained.

Perrot and Grenier [93] used radial velocities and distances of the molecular clouds based on a three-dimensional model for the evolution of the expanding shell and obtained results that are, on the whole, in satisfactory agreement with the Olano model [96]. Somewhat different parameters of the ellipse, $\approx 373 \times 233 \times 30$ pc with a center at $l_0 = 180^\circ$ and $R_0 = 104$ pc were obtained, as well as a substantially lower estimate for the mass of hydrogen (Table 1). They reached the interesting conclusion that the current geometric and kinematic characteristics of the Gould belt are essentially independent of the initial rotation direction. Confirming Blaauw’s opinion [100], they note the following contradiction. The explosion model assumed that the older OB associations were formed as a result of the interaction of a faster shock wave than the younger ones. This means that the older associations must lie further from the center of the explosion and move at higher speeds than the younger ones. However, the expected velocity gradient and distances are not observed in the Scorpio-Centaurus (US, UCL, and LCC) and Orion (Ori 1a, Ori 1b, and Ori 1c) associations, for which reliable estimates of the age of the individual groups are available.

Palouš [103] has modelled three cases in the framework of the explosion scenario: (a) free expansion from a point center, (b) the development of a shell similar to that observed around the OB associations, and (c) the development of a shell that appears as the result of the explosion of a hypernova (a powerful explosion resulting, for example, from the merger of two neutron stars). This author concludes that the observed characteristics of the Gould belt, specifically the Oort constants and the shape of the belt, cannot be explained in terms of these models. In case (a) the Oort constant $B$ remains equal to 0 during the evolution of the shell; in case (b) the shell does not break up into fragments,
in conflict with observations; and, in case (c) the development of the shell leads to a very prolate figure which agrees very poorly with the observed shape of the Gould belt.

Based on a comparison of observational data on stars with models of the expansion of the Gould belt in Refs. 91 and 104, the authors conclude that the expansion is more likely from a line, than a point center.

In the explosion model the following points are not clear: why the complex of molecular clouds in Taurus lies inside the expanding Lindblad ring (see Fig. 4) and what kind of role a magnetic field may play in bubble formation [26].

Nevertheless, digressing from the physical causes of the initial interaction with the parent cloud, it is possible reproduce the major features of the further evolution of the Gould belt. For example, based on a numerical simulation of the dynamic evolution of the Gould belt in a suitable galactic potential, Vasil’kova [105] has shown that an initial spherical distribution of the model particles becomes ellipsoidal with time (in accord with Blaauw’s earlier results) and that collective oscillations of the particles along the z axis occur which are typical of the Gould belt.

### 3.2 High-velocity clouds

Surveys of the distribution and motion of hydrogen show that the velocities of almost all the high-latitude hydrogen clouds are such that they converge toward the Galactic plane, and in a number of cases their velocities reach 200 km/s or more. Although the distances to these clouds are poorly known, it is assumed that they are associated with the Magellan flow [106,107].

Lépin and Duver [108] have proposed that a number of the large complexes of molecular clouds which lie sufficiently far from the galactic plane could be formed as a result of a collision of high-velocity clouds with the Galactic disk. A simple two-dimensional magnetohydrodynamic model was used to explain the appearance of such observed clusters of molecular clouds as Ori, Cha, r Oph, and Tau-Aur. Each cluster was treated separately, so that a structure such as the Gould belt could appear randomly in this model.

Comerón and Torra [109,104] have examined a more complicated model of oblique incidence of a high-velocity cloud on the galactic plane. They showed that a structure similar to the Lindblad ring ultimately forms, but with considerably larger dimensions. As Pöppel [26] noted, the study of these processes is of great interest for understanding the origin of the Gould belt, although the models proposed thus far encounter a number of problems in explaining some of the properties of the interstellar medium.

It is interesting to note the model of Bekki [110], which is similar to the model of Comeron and Torra, but involves a cloud of dark matter instead of a high-velocity hydrogen cloud. Bekki’s numerical simulations show that the Gould belt could have been formed about 30 million years ago from an initial gas cloud with a mass of about $10^6 M_\odot$ after a collision with a clump of dark matter with a mass of $3 \times 10^7 M_\odot$. In the calculations, the clump of dark matter moves from the southern into the northern hemisphere at an angle of about $30^\circ$ to the galactic plane. Its dynamic influence is such that a star formation process starts in an initially symmetric gas cloud (the parent of the Gould belt), the cloud gradually elongates into an ellipse, and finally acquires the dimensions and inclination to the galactic plane characteristic of the Gould belt.
3.3 Evolution of the Orion arm

In a paper by Olano [44] the Local system is identified with the Local arm (Orion arm) and the evolution of this structure with a mass of $2 \times 10^7 M_\odot$ is modelled over the last 100 million years. In this approach the gas moves at a high initial velocity ($\approx 50$ km/s) and the Local system is formed from it. It is assumed that this velocity could be achieved by an interaction with the Carina-Sagittarius arm. A collision of a gas cloud with a spiral density wave would lead to its breakup. In terms of this model, such clusters as the Hyades, Pleiades, and Coma Berenices, and the Sirius cluster are treated as fragments of a once unified complex and the compression of the central regions of a parent cloud led to the formation of the Gould belt. The construction of orbits with different structures in the Orion arm led to an interesting result: it turned out that the gravitation of the Local system has a significant effect on the sun’s motion.

4 Conclusion

At present there is a large scale earthbound survey of the sky (RAVE) under way for the purpose of determining the radial velocities of hundreds of thousands of stars, as well as a space experiment (GAIA) which will yield an enormous base of high-precision data on the distances and proper motions of millions of stars with microsecond accuracy, their radial velocities with accuracies of a fraction of a km/s, and their photometry. VLBI observations of galactic masers are continuing for the purpose of determining their proper motions and trigonometric parallaxes with high accuracy. These projects are primarily intended for studying the structure and kinematics of the Galaxy, since they will significantly expand the possibilities for studying the three-dimensional motions of stars lying at distances of up to 10 kpc from the sun.

As for studies of the Local system, the availability of high accuracy data should primarily enable reliable separation of objects in the Gould belt and Orion arm from the surrounding background in terms of an entire series of parameters – age, distribution, distance, kinematics. As a whole, this will aid in solving some of the following problems:

- clarifying the reasons for the initial interaction (or set of these) which led to the compression of a parent gas cloud from which the Orion arm and the Gould belt were formed;
- constructing an adequate dynamic model for the evolution of the Orion arm and the Gould belt; and,
- a detailed reconstruction of the history of star formation within the Local system.

A theory of the origin of the Gould belt should explain the following: its inclination; the distribution of the OB associations systems of molecular clouds surrounding it; the features of its three-dimensional velocity distribution; and, aid in clarifying its gravitational coupling.

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