THE KINEMATICS AND NATURE OF GOULD'S BELT – A 30 MYR OLD STAR FORMING REGION

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ABSTRACT

For a sample of 2440 non-supergiant Hipparcos stars belonging to Strömgren's 'early group' luminosities, temperatures, ages and distances have been determined. 241 stars younger than 30 Myr with well determined ages and space velocities fall within the local flattened system, inclined 20° to the galactic plane, called Gould's Belt. The system is dominated by a number of nearby prominent associations within a distance of 700 pc, foremost the Scorpius-Centaurus and Orion associations.

We derive galactic rotation parameters for young stars of ages less than 30 Myr situated outside the Gould Belt region. This gives a flat rotation curve with a circular angular velocity at the Sun of $\Omega_c = 25.3 \pm 1.5$ km s^{-1} kpc^{-1}.

The kinematics of Gould's Belt differs significantly from that of stars outside the system. Besides a slight outwards motion of a few km s^{-1} it rotates in the same direction as the galactic rotation and expands, giving apparent values for the galactic rotation parameters of $B = -21$ and $K = +12$ km s^{-1} kpc^{-1}.

It is suggested that this system was born about 30 − 40 Myr ago, possibly in a spiral arm, with an angular momentum too large to keep the system gravitationally bound. The rotation may explain the flatness of this inclined system.

Key words: local kinematics; Gould's Belt; galactic rotation; stellar associations.

1. INTRODUCTION

As is well known, a series of investigations, pioneered by Plaskett (1930) and Blaauw (1946), have shown that early type stars in the solar neighbourhood, within some 500 pc, show a different space distribution and kinematic behaviour from early type stars at larger distances. This local system of young stars, inclined 20° to the galactic plane, is referred to as Gould's Belt. Of investigations of the kinematics of Gould's Belt we will here refer to those by Westin (1985) and more recently by Mestres (1996) and by Torra et al. (1997). Lindblad et al. (1973) and Sandqvist et al. (1988) identified a local component of interstellar hydrogen and dust related to Gould's Belt.

Very different interpretations of the deviating character of Gould's Belt have been suggested in the literature.

2. SELECTION AND CALIBRATIONS

We selected those stars in the Hipparcos Catalogue for which complete Strömgren u, v, b, y and $H\beta$ photometry was available and that belong to Strömgren's 'early group' (Strömgren 1966), closely following the scheme given by Westin (1985). The Strömgren photometry was corrected for interstellar reddening following mainly the procedure of Shobbrook (1983). Absolute visual magnitudes M_V were computed using relations given by Balona & Shobbrook (1984). Distances were derived from M_V and the V magnitudes given in the HIP, corrected for reddening. Effective temperatures and bolometric corrections were computed according to the scheme for early group stars given by Balona (1994). Ages of the stars were then determined by interpolation in the tables of star models by Maeder & Meynet (1988).

It should be stressed that in this sample supergiants were excluded because the reddening corrections applied will not be accurate for supergiants. Also excluded were stars, where the possible variation in the Hipparcos magnitude system $Hp > 0.6$ mag, and double stars with a magnitude difference between components $\Delta Hp < 1.23$ mag, as well as stars with a relative error in distance > 0.3 or estimated error in age determination > 20 Myr. This results in a total sample of 1605 stars belonging to the 'early group'. In the kinematic analysis we exclude stars with error in proper motion > 2 mas/yr, and error in radial velocity > 20 km/s, which brings down the sample with relatively accurate space velocities to 1222 stars.

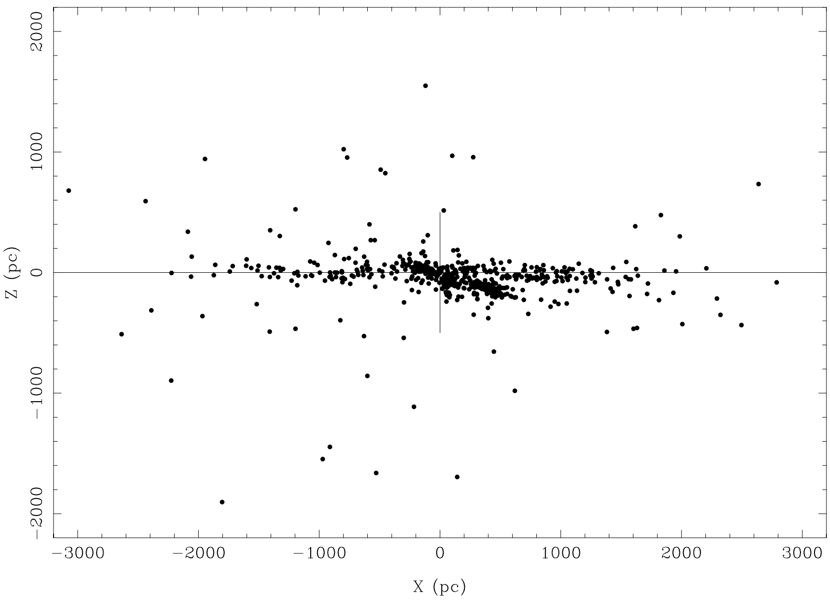

Figure 1. Spatial distribution of 593 stars in our sample younger than 30 Myr. The Sun is in the centre of the coordinate system. The X axis points towards the galactic anticentre and the Z axis is normal to the galactic plane.

3. SELECTION OF GOULD BELT STARS

In the present kinematic study we prefer to select the stars belonging to Gould's Belt purely on the basis of their peculiar spatial distribution. Figure 1 shows the spatial distribution of the stars in our sample younger than 30 Myr.

In this figure the inclined Gould's Belt can be spotted as the disturbance in the Z distribution for $|X| < 500$ pc. After a careful study of the distribution for a number of age and spatial intervals we suggest the following criteria for membership of Gould's Belt:

- age < 30 Myr
- position within the box given in Figure 2 defined by
  $-450 - Y < X < 600 - Y$
  $-450 + Y < X < 990 + Y$
- distance from the galactic plane < 500 pc.

As can be seen in Figure 2, the system is dominated by a number of nearby prominent associations within a distance of 700 pc, foremost the Scorpius-Centaurus and Orion associations. The projection of the Gould Belt stars selected in this way on the sky in galactic coordinates is shown in Figure 3.

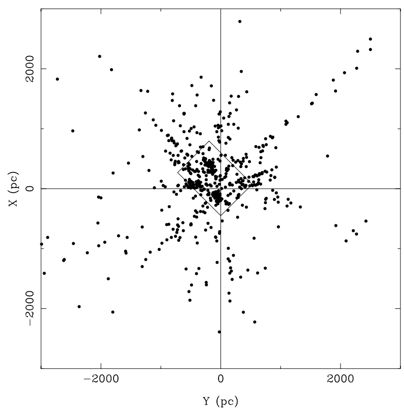

Figure 2. Spatial distribution of 560 stars in our sample younger than 30 Myr and with Z < 500 pc. The Sun is in the centre of the coordinate system. The X axis points towards the galactic anticentre and the Y axis in the direction of galactic rotation. The rectangular box shows the adopted limits for the Gould Belt region.

4. CONDITION EQUATIONS

The radial velocities and proper motions, together with the distances, are used to derive the velocity field around the Sun. For space velocities U, V, W, where the components are directed away from the galactic center, in the direction of the galactic rotation and perpendicular to the galactic plane, respectively, the linear part of the velocity field may be described by the solar motion $U_\odot, V_\odot, W_\odot$ and the nine gradients $\partial U/\partial X, \partial U/\partial Y, \partial U/\partial Z$, etc.

As we have proper motions for many more stars than for which we have radial velocities, it may be of advantage instead to use the expression for the radial

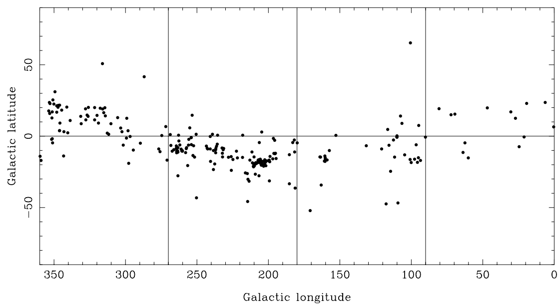

Figure 3. Galactic coordinates for the 249 stars in our sample selected to belong to Gould's Belt.

velocities (V_r) and the two galactic components of proper motion ($\mu_l \cos b$, μ_b):

$$V_r = U_\odot \cos l \cos b - V_\odot \sin l \cos b - W_\odot \sin b + r \cos^2 b\ (K + A \sin 2l + C \cos 2l) \quad (1)$$

$$4.74\ r\ \mu_l \cos b = -U_\odot \sin l - V_\odot \cos l + r \cos b\ (B + A \cos 2l - C \sin 2l) \quad (2)$$

$$4.74\ r\ \mu_b = -U_\odot \cos l \sin b + V_\odot \sin l \sin b - W_\odot \cos b - r \sin b \cos b\ (K + A \sin 2l + C \cos 2l) \quad (3)$$

where l, b are the galactic longitude and latitude, r is the distance from the Sun and:

$$A = -\frac{1}{2}\left(\frac{\partial U}{\partial Y} + \frac{\partial V}{\partial X}\right) \quad (4)$$

$$B = \frac{1}{2}\left(\frac{\partial U}{\partial Y} - \frac{\partial V}{\partial X}\right) \quad (5)$$

$$C = \frac{1}{2}\left(\frac{\partial U}{\partial X} - \frac{\partial V}{\partial Y}\right) \quad (6)$$

$$K = \frac{1}{2}\left(\frac{\partial U}{\partial X} + \frac{\partial V}{\partial Y}\right) \quad (7)$$

The development in Equations 1 to 3 is restricted to first order terms in the distance, and due to the flatness of the galactic disc gradients in the Z direction have been left out.

5. YOUNG STARS OUTSIDE GOULD'S BELT

To investigate the velocity field for young stars in the galactic plane but *outside* Gould's Belt we select stars situated outside the box of Figure 2, within 500 pc of the galactic plane, and within 2000 pc in distance projected on the plane. Table 1 gives the results of an analysis using a combination of the Equations 1 to 3. In this analysis the stars have been divided into three different age groups − younger than 30 Myr, between 30 and 60 Myr and all ages represented within the sample. In this last group there are 142 stars younger than 30 Myr, 55 stars 30–60 Myr and 94 stars older than 60 Myr.

Table 1. Galactic rotation parameters for young stars in the galactic plane outside of Gould's Belt.

Age (Myr)	0 − 30	30 − 60	all
N	142	55	291
$U_\odot$	−4.6 ± 1.0	−7.4 ± 1.3	−7.2 ± 0.6
$V_\odot$	11.8 ± 1.0	10.1 ± 1.3	10.4 ± 0.7
$W_\odot$	7.4 ± 0.6	7.9 ± 0.7	6.3 ± 0.3
A	12.8 ± 1.2	14.7 ± 2.3	13.7 ± 1.0
B	−12.5 ± 0.9	−16.8 ± 1.6	−13.6 ± 0.8
C	0.0 ± 1.4	3.6 ± 2.4	0.8 ± 1.1
K	−0.4 ± 1.4	−4.1 ± 2.0	−1.1 ± 0.8

As is seen, the differences between the three groups are marginal. The youngest group may have a slight inward motion of a few km s^{-1} compared to the older stars. The young stars of ages less than 30 Myr show clear evidence of circular motion with a locally flat rotation curve and a circular angular velocity at the Sun of $\Omega_c = 25.3 \pm 1.5$ km s^{-1} kpc^{-1}.

Introducing velocity gradients depending on Z in Equations 1 to 3 did not give significant improvement. A solution adding higher order terms of r to the same equations and including stars at $r > 2$ kpc did not give significant results for the coefficients of these higher order terms.

6. GOULD'S BELT

For stars within the Gould Belt region the corresponding solution encounters difficulties because of the small extension of the region, the eccentric position of the Sun and the very clumpy spatial distribution of the stars.

Solutions using Equations 1 and 2 separately and 1 to 3 in combination are given in Table 2. In those solutions stars with an error of the radial velocity > 2 km s^{-1} have been discarded. Notable is the large negative value of B and the significant positive value

Table 2. Galactic rotation parameters for young stars within the Gould Belt region.

N	144			9 (ass.)
Eq.	(2)	(1)	(1–3)	(4–7)
$U_\odot$	−13.2 ± 0.84	−6.9 ± 1.5	−9.8 ± 1.0	
$V_\odot$	13.8 ± 0.9	17.6 ± 1.4	16.8 ± 1.0	
$W_\odot$		8.2 ± 3.2	6.2 ± 1.0	
A	7.8 ± 3.9	−11.5 ± 4.1	−6.1 ± 4.1	3.9
B	−19.8 ± 2.8		−20.6 ± 5.2	−22.8
C	−6.1 ± 4.3	6.2 ± 3.9	2.9 ± 3.7	14.5
K		14.7 ± 2.8	11.0 ± 3.5	11.4

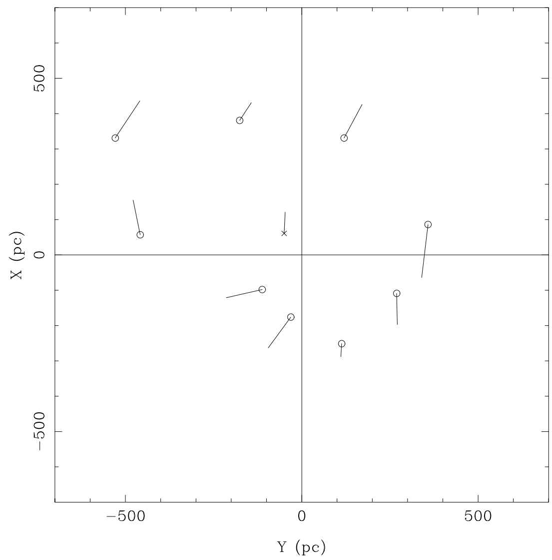

Figure 4. Spatial distribution of 9 apparent associations within Gould's Belt and their mean position (×). The vectors indicate the mean motion and the velocities relative to the mean in a non-rotating coordinate system.

of K. These agree very well with those derived by Westin (1985). Also Mestres (1996) gets a somewhat large negative value for B and a value for K that agrees well with ours. However, there are difficulties to get a set of A and C consistent for both the proper motions and the radial velocities, which is seen also in the analysis by Mestres. This may partly be due to the irregular distribution of stars and stellar groups, but it is also an indication that the velocity field even within this small region is non-linear.

As pointed out above, Gould's Belt is dominated by a few associations, predominantly in the third and fourth quadrants of galactic longitude. In order to decrease the errors and get a better impression of the velocity field within Gould's Belt we have identified, within different intervals of galactic longitude, dominating groups of stars with rather constant proper motion within a limited distance interval. These stellar groups and their average space motions projected on the galactic plane are shown in Figure 4.

A solution for the galactic rotation constants using Equations 4 to 7 for these nine groups gives the result in the last column of Table 2. Figure 4 indicates a clockwise rotation of the system, which is the cause of the large negative value of B. Also an expansion is seen which causes the positive non-zero value of K. It should be pointed out again that the dominating associations are the Scorpius-Centaurus association at $X = -170$ pc, $Y = -30$ pc and $X = -100$ pc, $Y = -110$ pc and the Orion association at $X = 380$ pc, $Y = -180$ pc plus an association of stars at $X = 60$ pc, $Y = -460$ pc.

7. DISCUSSION

It is of course a possibility that Gould's Belt is just a random configuration of two or three dominating associations concentrated in the third and fourth quadrants of galactic longitude, in particular the Scorpius-Centaurus and the Orion associations. The 'Finger of God' effect could help to give the impression of a flattened plane. However, there are arguments to see this assembly of stars as a coherent system with a common origin: (a) the position of the Orion association below the plane and the Scorpius-Centaurus association above the plane at the opposite galactic longitude would also have to be at random. Also there are more stars and associations than these two that give rise to the inclination; (b) Lindblad et al. (1973), Lindblad (1974), Olano (1982), and Sandqvist et al. (1988) show that there exists a local cloud or ring of H I and dust clouds (with velocities from H_2CO) which largely coincides with Gould's Belt as outlined here, shows a similar tilt to the galactic plane, and shows a similar expanding motion.

A consistent interpretation of the motions within the Gould Belt region is not available yet. The system moves away from the galactic center at ~ 5 km s^{-1}, it expands at a rate of about 12 km s^{-1}kpc^{-1}, and it rotates giving an apparent value for the galactic rotation parameter $B = -21$ km s^{-1} kpc^{-1}. However, there is not an agreement in the values of A and C from radial velocities and proper motions, and the velocity field may well be non-linear.

Selection of stars belonging to Gould's Belt purely on the basis of their spatial distribution should perhaps be abandoned and the kinematical information should also be used. The plane parallel space velocity components for stars younger than 30 Myr are plotted in Figure 5. Continuous turn of vectors in a stream-like velocity pattern shows that besides the Orion and the Scorpius-Centaurus associations also the OB associations in Cygnus should be included into the kinematical analysis (see also Hoogerwerf et al. 1997). This will be considered in future discussions. The figure confirms the impression of a non-linear velocity field.

It has been suggested (Lindblad et al. 1973) that this system was born after a compression of a giant molecular cloud of some 10^6 M$_\odot$ in a spiral arm $30 - 40$ Myr ago. After the first generation of stars was formed these stars dispersed while the interstellar matter was driven out by supernovae and stellar winds giving birth to later generations of stars in the process. The stars born, however, could not just have expanded from a small area in the field of differential rotation because this would have resulted in a value of $B = 0$, which is certainly contradicted by the observations. Thus, we suggest that the original cloud had an angular momentum which was too large to make the cloud gravitationally bound and causing the expansion.

The rotation of the system might be an explanation why it has been able to keep its flatness and appreciable inclination to the galactic plane over several times 10^7 years. This model is now being tested with numerical N-body calculations.

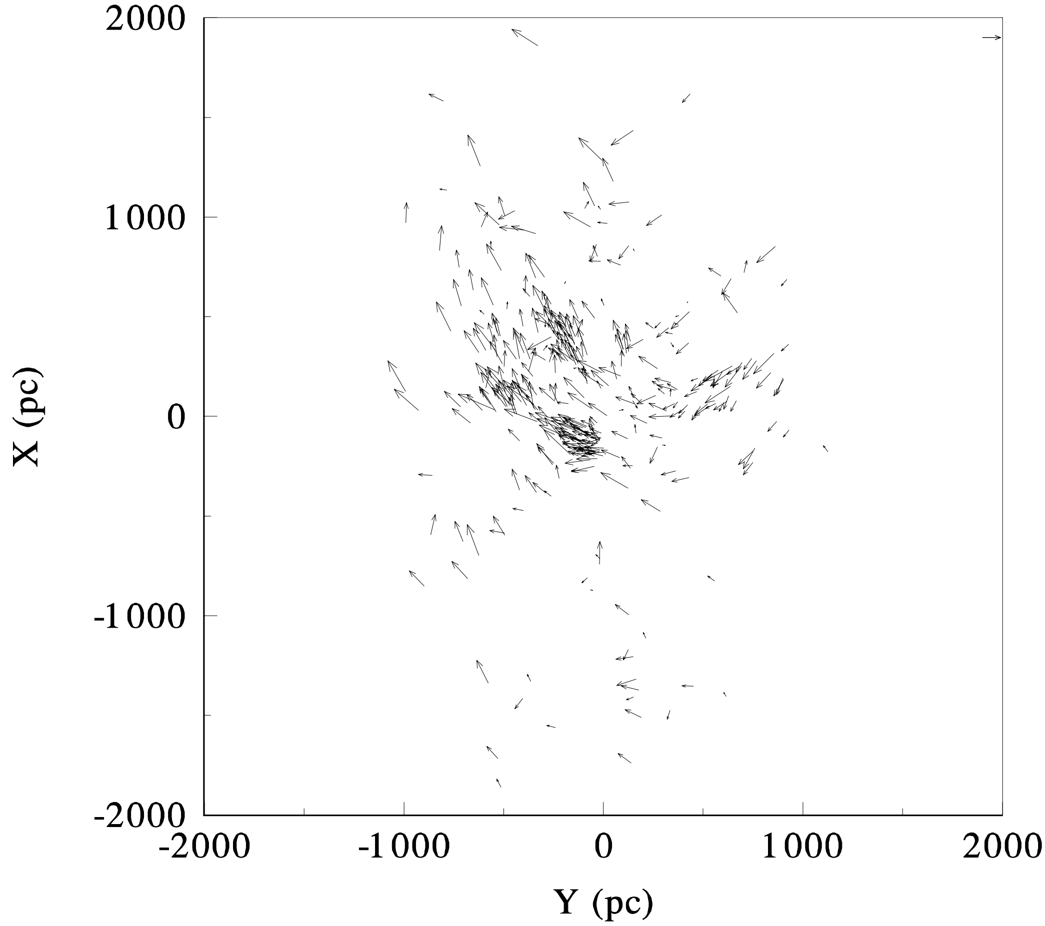

Figure 5. Space velocity vectors relative to the Sun projected to the galactic plane for 361 stars younger than 30 Myr. The arrow in the upper right corner is 20 km s^{-1} long.

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