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On the rotation of Gould's Belt

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Abstract. Among the characteristics that define the local system of stars called Gould's Belt are the flatness of the system, its inclination of about 20° to the galactic plane, and its expansion. This has to be conciled with its age being estimated at 30–40 Myr. The model, introduced here to explain the persistence of the tilt of the system to the galactic plane, is an inclined rotating and expanding disk. The model is developed in the linear approximation, and the parameters of the model are derived from the observations. The result gives a reasonable set of parameters. It is pointed out, however, that a final picture must be based on realistic non-linear simulations adding self-gravitation and successive birth of stars in an interstellar cloud, expanding due to actions of young stars and supernovae.

Key words: stars: early-type – stars: formation – Galaxy: kinematics and dynamics

1. Introduction

Gould's Belt is a local subsystem of early type stars in the Milky Way galaxy. It is distinguished by the following characteristics:

- It is flattened with an inclination of about 20° to the galactic plane and a line of nodes running roughly parallel to the direction of galactic rotation.
- Its radial distribution in the Galaxy, as judged from the deviation from the galactic plane, extends from about 300 pc in the centre direction to about 600 pc towards the anticentre, its extent in the tangential direction being more difficult to determine.
- Its kinematics differs markedly from pure circular differential rotation around the galactic centre and from that of older stars in the same region or young stars at larger distances. In particular, the presence of a significant K term indicates an expansion of the system.
- The characteristic behaviour is confined to stars younger than about 30–40 Myr.

The system contains substantial amounts of interstellar gas and dust. The connection of the very local component of interstellar matter to Gould's Belt is indicated by its distribution on the sky and kinematic behaviour. There is evidence that a population of faint γ-ray sources are associated with the Gould Belt (Gehrels et al. 2000).

A detailed review of the Gould Belt system has been given by Pöppel (1997).

2. Observational fundamentals of Gould's Belt

The orientation of the Gould Belt system in space and its spatial distribution has been the subject of numerous investigations. The result depends on the way members of the system are identified. Torra et al. (2000) derived an inclination to the galactic plane of 20° and a line of nodes running approximately along the 105° / 285° direction in galactic longitude, where $l = 285°$ is the node where the galactic latitude is increasing for increasing longitude. These values are in good agreement with others published in the literature.

In Fig. 1 the positions, projected on the galactic plane, of a sample of stars younger than 30 Myr have been plotted. The sample consists of stars from the Hipparcos catalogue with Strömgren and Hβ photometry for which errors in the derived distances and ages are less than 30% and 20 Myr respectively (Lindblad et al. 1997). The spatial distribution of Gould's Belt was derived by these authors as the region over which the inclination of the system is maintained for stars younger than 30 Myr. This region is indicated by a rectangular box in Fig. 1.

Studies of the kinematics of Gould's Belt based on Hipparcos proper motions and available radial velocities have been published by Lindblad et al. (1997) and Torra et al. (1997; 2000). Torra et al. derived values for Oort's constants A, B, C, K for a number of different age intervals. The results for stars with distances from the Sun between 70 pc and 400 pc from Torra et al. (1997) are reproduced in Table 1. These should be compared with the values $A = 14.4, B = -12.0, C = K = 0$ km s^{-1} kpc^{-1} for general galactic rotation in circular motions as derived by Kerr & Lynden-Bell (1986). As can be seen, Oort's constants take rather extreme values for small ages but have reached normal values for differential galactic rotation at ages of about 90 Myr. The variation is smoothed by the uncertainty in the age determinations and the gradual mixing of Gould Belt and non-Gould Belt stars as the age increases. Various estimates of Oort's constants for Gould's Belt differ primarily due to different ways to select member stars, to the variation of the constants with age within the system, and the non-linearity of the velocity variations over this limited system.

The gradient of the velocity v_z, perpendicular to the galactic plane, has been studied by Comerón (1999). He derives a

Table 1. Oort's constants (in units of km s^{-1} kpc^{-1}) as a function of age for stars with distances from the Sun between 70 and 400 pc (Torra et al. 1997)

Age (10^6 years)	age $<$ 20	20 $<$age$<$ 40	40 $<$age$<$ 60	60 $<$age$<$ 80	80 $<$age$<$ 100
A	-0.4 ± 4.6	7.5 ± 2.8	7.1 ± 3.2	12.0 ± 3.4	14.1 ± 4.0
B	-26.0 ± 4.6	-17.4 ± 2.8	-15.1 ± 3.2	-13.6 ± 3.4	-12.2 ± 4.0
C	3.1 ± 4.6	9.0 ± 2.8	6.8 ± 3.2	7.5 ± 3.4	2.0 ± 4.0
K	14.3 ± 4.6	10.1 ± 2.8	3.8 ± 3.2	-1.1 ± 3.4	-1.5 ± 4.0

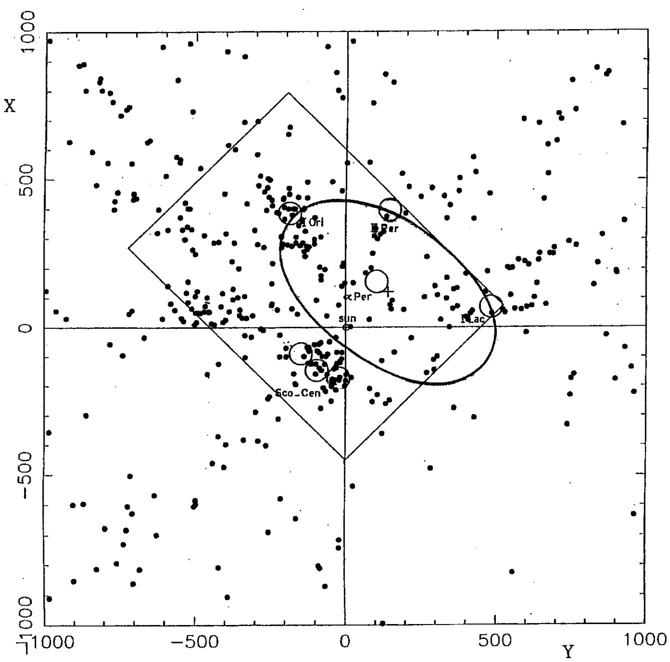

Fig. 1. Spatial distribution of stars in the solar neighbourhood younger than 30 Myr and within a distance from the galactic plane of 500 pc. The (vertical) X coordinate is directed towards the galactic anticentre and the (horizontal) Y coordinate towards the direction of galactic rotation and the scales are given in pc. The tilted rectangular box indicates the region within which the inclination to the galactic plane characterizing the Gould Belt system is maintained according to Lindblad et al. (1997). The ellipse indicates the expanding ring of neutral hydrogen according to the model of Olano (1982). Some neighbouring associations are indicated by small circles

maximum gradient of $\frac{dv_z}{dr} = 6.5 \pm 1.8$ km s^{-1} kpc^{-1} and an 'axis of vertical oscillation' directed towards galactic longitude $337° \pm 20°$, where r is the distance from the star to this axis projected on the galactic plane. The direction of the axis implies that the direction of maximum gradient is towards a longitude around $l = 337° + 90° = 67°$.

The kinematics of the very local, expanding component of interstellar neutral hydrogen that appears to be related to Gould's Belt has been studied by Lindblad et al. (1973). Its distribution on the sky has been mapped by Schober (1976) showing implicitly that, although the distribution in latitude is very wide, it has a mean inclination closely following that of Gould's Belt. Interstellar dust clouds along Gould's Belt on the sky share the kinematic behaviour of the neutral hydrogen gas as shown by formaldehyde line absorption (Sandqvist & Lindroos 1976). Lindblad et al. (1973), followed up by Grape (1975), interpreted the observations in terms of a slowly expanding ring or cloud of gas extending roughly over the region of Gould's Belt and with the Sun close to the edge of the system. These models were based only on stellar kinematics. Olano (1982) introduced a gas dynamical model with an explosive origin and with the expanding velocities braked by surrounding interstellar matter, resulting in a ring with similar shape as in the earlier investigations and an expansion age of about 30 Myr (Fig. 1). This model gave a total mass of the neutral hydrogen contained in the Gould Belt system of $1.2 \times 10^6 M_\odot$.

3. Kinematics of an inclined rotating and expanding system

In the different models that have been proposed to explain the observed behaviour of Gould's Belt, one of the features that is not very satisfactorily explained is the origin and maintenance of the tilt of the system to the galactic plane that must have existed for the order of 30 Myr.

Lindblad et al. (1997) suggested that Gould's Belt is rotating, and that the rotation of a self gravitating system is the explanation why it has been able to keep its flatness and inclination over such a long time. Also, that this cloud had an angular momentum and velocity dispersion too large to make the cloud gravitationally bound and that it is thus expanding.

Palouš (1997) derived galactic rotation constants in an N-body simulation of a disk in the galactic plane in Keplerian rotation around a local mass too small for rotational equilibrium. Comerón (1999) considers a system initially in solid body rotation. This system is not self-gravitating and thus its flatness and tilt is depending on in-phase vertical oscillation.

We will here study an inclined rotating and expanding disk as a basic explanation to the kinematic characteristics of the system.

3.1. Fundamental equations for the planar velocity gradients

Consider a stellar subsystem with the shape of a flattened disk which is rotating with its axis of rotation perpendicular to the plane of the disk and radially expanding in directions parallell to that plane. We introduce

R distance of a star from the centre of rotation, projected on the plane of the disk,

$\omega(R)$ angular velocity of rotation, counted positive if in the same sense as the galactic rotation,
$v_R(R)$ velocity of expansion radially from the centre of rotation, projected on the plane of the disk,
$\rho(R) = \frac{v_R}{R}$ expansion rate.

This system is studied by an observer within the disk at a distance R_o from the centre of rotation and whose local standard of rest participates in the rotation of the stellar subsystem. We introduce $\omega_o = \omega(R_o)$ and $\rho_o = \rho(R_o)$. We further introduce

l a longitudal coordinate along the disk at which a star in the subsystem is observed. l is counted positive in the same sense as the galactic longitude,
r distance to the star observed, projected on the plane of the disk,
l_o longitudal coordinate of the centre of rotation of the subsystem,
v_r radial velocity of the star along the line of sight, projected on the plane of the disk,
v_l tangential velocity component of the star parallel to the plane of the disk and counted positive for increasing longitude.

We then get

$$v_r = (\omega - \omega_o)R_o \sin(l - l_o) - (\rho - \rho_o)R_o \cos(l - l_o) + \rho r \quad (1)$$

$$v_l = (\omega - \omega_o)R_o \cos(l - l_o) + (\rho - \rho_o)R_o \sin(l - l_o) - \omega r \quad (2)$$

Let us introduce

$$A_\omega = -\frac{1}{2}R_o \left(\frac{d\omega}{dR}\right)_{R=R_o}$$

$$A_\rho = -\frac{1}{2}R_o \left(\frac{d\rho}{dR}\right)_{R=R_o}$$

Taking the derivatives of Eqs. (1) and (2) we get, for r = 0, the local velocity gradients

$$\frac{dv_r}{dr} = A_\omega \sin 2(l - l_o) - A_\rho \cos 2(l - l_o) + \rho_o - A_\rho \quad (3)$$

$$\frac{dv_l}{dr} = A_\omega \cos 2(l - l_o) + A_\rho \sin 2(l - l_o) - \omega_o + A_\omega \quad (4)$$

Defining

$$A = A_\omega \cos 2l_o - A_\rho \sin 2l_o \quad (5)$$

$$-B = \omega_o - A_\omega \quad (6)$$

$$C = -A_\omega \sin 2l_o - A_\rho \cos 2l_o \quad (7)$$

$$K = \rho_o - A_\rho \quad (8)$$

the Eqs. (3) and (4) can be written in the usual form

$$\frac{dv_r}{dr} = A \sin 2l + C \cos 2l + K$$

$$\frac{dv_l}{dr} = A \cos 2l - C \sin 2l + B$$

3.2. The vertical velocity gradient

If the plane of the rotating system is inclined to the galactic plane, there will be systematic motions in the z direction perpendicular to the galactic plane.

Introduce

i angle of inclination between the plane of the rotating system and the galactic plane,
ϕ angle, centered at the centre of rotation, counted in the plane of the rotating system from the ascending node to a star, and increasing in the direction of rotation,
v_z velocity perpendicular to the galactic plane of the star relative to the velocity of the centre of rotation.

We then have

$$v_z = R(\omega \cos \phi + \rho \sin \phi) \sin i.$$

The direction ϕ_o of maximum v_z for a given R is then given by

$$\tan \phi_o = \frac{\rho}{\omega}$$

and

$$\left(\frac{v_z}{R}\right)_{max} = \sqrt{\omega^2 + \rho^2} \sin i \quad (9)$$

For pure circular rotation ($\rho = 0$) the direction of ϕ_o coincides with the line of nodes. The angular deviation from the line of nodes projected on the galactic plane, ψ, is given by

$$\tan \psi = \cos i \tan \phi_o = \cos i \, \frac{\rho}{\omega} \quad (10)$$

The longitude of maximum v_z, as given by ψ and the line of nodes, is perpendicular to the 'axis of vertical oscillation' as defined by Comerón (1999).

3.3. Model parameters derived from observations

The parameters $A, B, C, K, \psi, (\frac{v_z}{R})_{max}$, and i may be derived from observations and are thus 'known'. Exchanging ρ, ω for ρ_o, ω_o in Eqs. (9) and (10) the six Eqs. (5) to (10) then form an over-determined system to derive the five unknown parameters $\omega_o, \rho_o, l_o, A_\omega$, and A_ρ.

As the younger associations in Gould's Belt seem to surround the system in a ring-like structure, we assume that the rotating disk will be made up of the older stars of Gould's Belt formed as a result of the original compression. Thus, we choose the age group 20–40 Myr from Table 1 to represent the population of the rotating disk. The Oort constants in the table are derived with reference to the galactic plane and not to the plane of Gould's Belt. We ignore this inconsistency in the following which can be considered as a very preliminary derivation of the unknown parameters. With $i = 20°$ and the direction of the line of nodes, $l = 285°$, given by Torra et al. (2000) we get from the direction of the maximum radial gradient of vertical motion, $l = 67°$, derived by Comerón (1999) $\psi = 285 - 180 - 67 = 38°$. From the five Eqs. (5) to (8) and (10) we then can solve for the five unknowns. This leads to a quadratic equation in ω_o, and we

Table 2. Parameters for a rotating and expanding disk

Solution	Nr. 1	Nr. 2
$\omega_o(\mathrm{km\,s^{-1}kpc^{-1}})$	24	6.6
$\rho_o(\mathrm{km\,s^{-1}kpc^{-1}})$	20	5.5
$A_\omega(\mathrm{km\,s^{-1}kpc^{-1}})$	6.4	-11
$A_\rho(\mathrm{km\,s^{-1}kpc^{-1}})$	9.7	-4.6
l_o	127°	53°
$\left(\frac{v_z}{R}\right)_{\max}(\mathrm{km\,s^{-1}kpc^{-1}})$	11	3

get the two solutions given in Table 2. These solutions inserted into Eq. (9) give $\left(\frac{v_z}{R}\right)_{\max}$ as presented in the last line of Table 2.

The signs of ω_o imply that the system rotates, in a fixed frame of reference, in the same direction as the galactic rotation.

For solution Nr. 1 this angular velocity is about the same as that of galactic rotation, and the positive signs of A_ω and A_ρ imply that both the angular velocity and the expansion rate decline with distance from the centre of rotation. The value of $l_o = 127°$ should be compared with the longitude $l_o = 131°$ derived by Olano (1982) for the direction to the centre of the expanding neutral hydrogen ring.

For solution Nr. 2 the value of ω_o implies that the system rotates much slower than the galactic rotation. The negative values of A_ω and A_ρ indicate an increase outwards of both angular velocity of rotation and expansion. Further, the direction towards the centre of rotation differs appreciably from that given by models of the distribution of interstellar matter. For these reasons we consider this second solution as less likely to correspond to reality.

In both cases the values of $\left(\frac{v_z}{R}\right)_{\max}$ deviate somewhat, but probably not significantly, from the value 6.5 km $\mathrm{s^{-1}}$ $\mathrm{kpc^{-1}}$ given by Comerón (1999).

4. Discussion

We envisage Gould's Belt as a flat rotating and expanding system of young stars. The rotation and expansion are governed by the initial angular momentum and the gravitational attraction of the system itself. The rotation must be sufficiently large that differential precession, due to forces perpendicular to the galactic plane, do not appreciably distort the flattened system within a time span of 30 Myr.

Adopting a force law perpendicular to the galactic plane given by Bahcall (1984, see his Fig. 7, solid curve), we get for solution Nr. 1 a precession of the line of nodes at the edge of the system of the order of 12° $\mathrm{Myr^{-1}}$. The differe ntial precession at the edge would be about 60° over 30 Myr and a distance interval of 100 pc. This gives a warp of the system of 17° in inclination over a distance interval of 100 pc at the edge. This significant warp would be reached in the di rection of the nodes in the galactic plane and, maybe, not easy to clearly recognize.

If we adopt the distance to the centre of the Gould Belt system of 166 pc, as given by Olano (1982) for the distance to the centre of the neutral hydrogen ring, the tangential and expansional velocities at the position of the Sun would be 4.0 and 3.3 km $\mathrm{s^{-1}}$, respectively, and the total velocity 5.2 km $\mathrm{s^{-1}}$ in the case of solution Nr. 1. To the order of magnitude this seems reasonable when compared to the velocity of 5.1 km $\mathrm{s^{-1}}$ for a circular orbit around a central mass of $10^6 M_\odot$ at the same distance.

If the original contraction of the mass that was to become the Gould Belt system took place in a large scale galactic shock in a spiral arm, this shock might be unstable and break up in parts of the order of $10^6 M_\odot$. (Other scenarios for the origin of Gould's Belt have been suggested, see Comerón 1999.) The resulting stellar system formed would presumably have an angular momentum, but the total mass may not be sufficient to keep the system bound. The direction of the angular momentum vector could be of random origin. Harten (1971) has shown that the large scale gas motion, in all the main spiral features in the Galaxy, displays systematic velocity gradients in the direction perpendicular to the galactic plane. He interprets this as the effect of a combination of tumbling and shear motions. This implies that the angular momenta of interstellar cloud complexes in spiral arms commonly would not be aligned with the rotation axis of the Galaxy.

In view of the uncertainties of the observed quantities and the linearisation implied in the derivation of velocity gradients, the parameters of the models in Table 2 should not be taken too literally but rather serve as indications of what kind of model would be derived and for judgement of how reasonable the basic idea behind the model may be. The values of the derived parameters are in many cases rather sensitive to the values adopted for the observed ones. The linear approach made here is not quite valid and the velocity field over this limited system is not well described by linear velocity gradients (see Fig. 5 of Lindblad et al. 1997). Lindblad et al. (1997) suspected this to be a reason why Oort's constants derived from different kinds of observations could differ rather much.

An adequate test of the model should involve the following steps:

– The velocity field of Gould Belt stars with an age comparable with the age of the system should be compared to numerical simulations of a rotating selfgravitating system within a galactic potential.
– Olano's (1982) model for the expanding interstellar gas should be improved in two respects. The initial expansion should be complemented with a force pushing the gas due to stellar winds from a number of supernovae and bright stars. Further, one should realise that the braking interstellar medium is itself expanding in a density wave streaming motion.
– The associations which contain a large fraction of the youngest group in Table 1, i.e. stars of ages younger than 20 Myr, seem to lie in a ring roughly coinciding with that of the gas. They presumably have been formed out of this gas during its expansion. A simulation where the youngest stars have been born out of the gaseous ring during its expansion should, if the picture is right, be able to reproduce the kinematic behaviour of these stars within Gould's Belt.

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