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Vertical motion and expansion of the Gould Belt

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Abstract. The kinematics of the Gould Belt is considered taking into account its orientation in space and the motions of its member stars parallel and perpendicular to the galactic plane. An analysis of *Hipparcos* data for these stars, complemented with published radial velocities, shows that there is a mild gradient along the galactic plane in the velocity component perpendicular to it. The maintenance of the arrangement of Gould Belt stars forming a plane, even for times that are at least a considerable fraction of the vertical oscillation period of stars around the galactic plane, is a rather strong constraint on any kinematical models of the Gould Belt. It is shown that such a constraint can be satisfied if the stars had initial velocities linearly dependent on their positions in the plane of the Belt. Adopting such linear patterns and the epicyclic approximation to galactic orbits, analytical expressions are derived that allow the calculation, for any age of the Gould Belt, of the direction of its nodal line, its inclination, the values of the Oort constants A, B, C, and K, the gradient of the velocity component perpendicular to the galactic disk, and the direction of the axis of oscillation of the stars of the Belt perpendicular to the galactic plane. The evolution of all these quantities is calculated for several cases: a purely circular motion of the Gould Belt stars around the galactic center; the radial expansion from a small volume or over an extended area; the expansion along a line; and an initial rotation to the Gould Belt stars around an axis perpendicular to its plane. Pure expansion models seem to be ruled out by observations, as none of them, under any combination of initial parameters, is able to simultaneously reproduce all the observed values of the orientation, the Oort constants, and the characteristics of the vertical motion. Nevertheless, a good agreement is found between measured values of the quantities defining the orientation and kinematics of the Gould Belt, and the predictions of the rotation model. This model is the only one among those considered here able to account for the large observed offset between the nodal line of the Gould Belt with respect to the galactic plane and the axis of vertical oscillation of its stars. The best fit is achieved for an age of the Gould Belt of $(3.4 \pm 0.3) \times 10^7$ years, consistent with individual ages determined for Gould Belt stars. The implications that the rotation model has concerning the possible origin of the Gould Belt is briefly discussed. It is found that the disruption of a rotating, star forming giant molecular cloud is unlikely to be at the origin of the Gould Belt, due to the significant tilt with respect to the direction perpendicular to the galactic plane that it should have had.

Key words: Stars: early-type, kinematics; the Galaxy: kinematics and dynamics, solar neighbourhood; open clusters and associations: Gould Belt

1. Introduction

The most distinctive and intriguing feature of the Gould Belt system of young stars and star forming regions is its tilt of 20° with respect to the galactic equator. Several models for the origin of the Gould Belt exist in the literature, such as those based on the fragmentation of a large molecular complex, on propagating star formation triggered by supernovae, the compression of gas during the passage of a spiral density wave, or the collision of high velocity gas with the galactic disk (see Pöppel 1997 for a comprehensive review). However, few of these models have explicitly addressed the question of the origin of the tilt. Observations of the distribution of the stars in the Gould Belt show that the tilt is preserved at least over the distance from ρ Ophiuchi to the Orion molecular complex, the two star forming regions which delimit the extent of the Belt in the galactocentric and antigalactocentric directions (roughly coinciding with its apsidal line), implying a coherence over a lengthscale of about 700 pc. This coherence, and the very existence of the Gould Belt as a single entity, have been eventually called into question by authors who noted that the distribution of stars in the Belt is apparently dominated by a few major structures which might have independent origins, and whose arrangement along a tilted disk may be casual (Franco et al. 1988, Lépine & Duvert 1994; see also Guillout et al. 1998). In-

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deed, most of the early-type stars that make the Gould Belt outstanding belong to the OB associations of Orion, Perseus OB2, and Scorpius-Centaurus-Lupus (Blaauw 1991, de Zeeuw et al. 1999). However, the existence of a distributed population of young stars not associated with any of the massive star forming complexes is revealed for instance by the sky distribution of young, chromospherically active low mass stars detected in the ROSAT all-sky survey (Neuhäuser 1997, Guillout et al. 1998). Moreover, the precise three-dimensional picture of the stellar distribution in the solar neighbourhood provided by the *Hipparcos* satellite clearly shows the existence of a distributed population of B stars that depict the Gould Belt as a disk with its members spread well outside the boundaries of the known OB associations. As shown by Torra et al. 1999, the kinematical peculiarities distinctive of the Gould Belt are preserved even when the stars belonging to the dominant associations are excluded from analyisis. On the other hand, the overall age of the Gould Belt, although very uncertain (published estimates range between 20 and 90 million years; see Torra et al. 1999 for a review of determinations found in the literature), is in any case at least a considerable fraction of the vertical oscillation period of stars around the galactic plane under the effects of the galactic gravitational potential, implying that the coherent structure of the Belt applies not only to the position of its components, but to their motions as well.

In this paper I intend to make a schematic exploration on the implications that the maintenance of the coherence with time of the structure of the Gould Belt has when combined to its kinematics, stressing the importance of stellar motions perpendicular to the galactic plane when interpreting measured velocity gradients. I will first present evidence for a systematic pattern of the vertical components of stellar motions, revealed by the *Hipparcos* data. Using the epicyclic approximation to the orbits of the stars in the galactic potential, I will then discuss the conditions under which an ensemble of stars, having an initial pattern of peculiar motions and being distributed on a tilted plane, can still define a plane as their trajectories evolve. The time evolution of the tilted plane with respect to the galactic equator, in particular its inclination, the position of its nodal line, and the different velocity gradients expected from its member stars, will be studied under the assumption of different initial patterns of motion. Finally, a global interpretation of the Gould Belt kinematics based on the actually observed orientation and velocity patterns will be discussed.

2. Observed vertical motions in the Gould Belt

The kinematic structure of the Gould Belt has been extensively studied for nearly one century now (see Frogel & Stothers 1977 for an exhaustive review, and Torra et al. 1999 for references to more recent, mostly pre-*Hipparcos* work). Most of the studies have explored the kinematical peculiarities of this structure on the basis of the velocity components of the stars in the directions of the galactic plane, as well as their gradients in those same directions. These motions reveal a rather complex expanding pattern associated to the Gould Belt. Torra et al. 1999 have carried out a comprehensive study of the kinematics of the Gould Belt using *Hipparcos* data, complemented with radial velocities and Strömgren photometry which enabled them to obtain space velocities and ages for a large sample of O and B stars. Similar analyses have been published by Lindblad et al. 1997 and Palouš 1998. These studies are also restricted to motions in the directions of the galactic plane only, and I will refer to their results for the forthcoming discussions on this aspect.

Studies on the velocity component perpendicular to the galactic plane have been much less abundant, probably due to the subtler systematic patterns that may be expected and to the little use of radial velocities in this case, as nearly all the stars lie at low galactic latitudes. Fortunately, the proper motions of unprecedented quality provided by *Hipparcos* make it possible now to carry out meaningful studies based on proper motions of stars with precisely known distances, out to a distance from the Sun comparable to the whole extent of the Gould Belt. To complement the results of the works referred to in the previous paragraph, I have prepared a sample of *Hipparcos* stars fulfilling the following requirements:

- Spectral types not later than B2.5, to ensure that only very young stars with the age of the Gould Belt or less are included.
- Relative error in the trigonometric parallax below 30%.

The second constraint implies in practice that nearly all the stars are found within a distance of 400 pc from the Sun, which matches fairly well the size of the Gould Belt. At that distance, the average standard error in the *Hipparcos* proper motion for the stars in the sample, $0''0009$ yr^{-1}, results in a velocity error of only 1.7 km s^{-1}, and is below 1 km s^{-1} for most of the stars in the sample. Therefore, no constrain has been set on the proper motions at the time of selecting the stars. To obtain space velocities, the sample has been complemented with radial velocities taken from the catalogues of Barbier 1989, Andersen & Nordström 1983a, 1983b, 1985, Duflot et al. 1995, and Fehrenbach et al. 1997. It should be noted however that, with most of the stars lying at galactic latitudes $|b| < 25°$, the radial velocity adds only a minor contribution to the velocity component perpendicular to the galactic plane discussed here. For this reason, the 20 stars without published radial velocities in the sample of 323 stars selected from the *Hipparcos* catalog have been retained, arbitrarily assigning them a zero radial velocity.

As shown by Torra et al. 1999, most of the stars with ages below 3×10^7 years in the solar neighbourhood (which approximately includes the sample used here) belong to the Gould Belt on the basis of their spatial distribution.

Therefore, kinematical contamination by stars not belonging to that structure is not expected to be significant in the present sample.

Let us assume that the perpendicular component of the velocity, W, has systematic variations along the galactic plane, expressed as $\partial W/\partial x$, $\partial W/\partial y$, where x is directed towards the galactic center and y towards the direction of galactic rotation. Such derivatives of W allow the definition of an *axis of vertical oscillation* of the stars around the galactic plane, $\boldsymbol{G}$, which has the property that W is proportional to the distance of the star to it:

$$W = |\boldsymbol{G} \times \boldsymbol{R}|_z \tag{1}$$

where the z subindex indicates the component along the direction perpendicular to the galactic plane, and $\boldsymbol{R}$ is the vector perpendicular to the axis of vertical oscillation joining it with the star. Eq. (1) can be written as

$$W = G_x y - G_y x + |G| R_0 \tag{2}$$

with x, y now being the components of the heliocentric position vector of the star in the directions defined above. R_0 is the distance of the nearest point of the axis of vertical oscillation to the Sun, which can be positive or negative depending on whether the x coordinate of that point is positive or negative. The sense of $\boldsymbol{G}$ is defined so that, if $G_y > 0$, then the stars located in the hemisphere, limited by the plane defined by $\boldsymbol{G}$ and the z direction, that faces the galactic center are moving towards decreasing z. The components of $\boldsymbol{G}$ are thus

$$G_x = \frac{\partial W}{\partial y} \quad , \qquad G_y = -\frac{\partial W}{\partial x} \tag{3}$$

An expression like Eq. (2) can be written for each star in the catalog, setting up a system with the unknowns G_x, G_y, and $|G|R_0$ that can be solved by least squares. Before doing that, however, it is necessary to consider the contribution to W due to the peculiar motion of the Sun, which otherwise would be engulfed in the last term on the right hand side of Eq. (2). Following Torra et al. 1999, I use $W_\odot = 8.0$ km s^{-1} as the value to add to the observed W before using it as the input for the left hand side of Eq. (2).

The solution of Eq. (2) for the sample of stars used here reveals indeed a significant systematic pattern in the vertical motions of the stars under study, yielding the following values:

$$|G| = 6.5 \pm 1.8 \text{ km s}^{-1} \text{ kpc}^{-1}$$

$$\alpha = 337^\circ \pm 20^\circ$$

$$R_0 = 210 \pm 105 \text{ pc}$$

where α is defined by

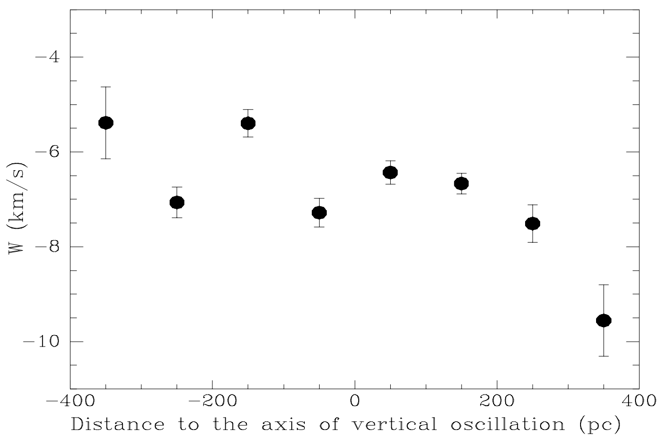

Fig. 1. The vertical component of the velocity, W (uncorrected for reflected solar motion), as a function of the distance to the axis of vertical oscillation. The cosmic dispersion of W considerably exceeds the systematic difference of velocities over the distance interval considered here. For this reason, the velocities averaged over 100 pc bins are plotted here, rather than the individual velocities. The error bars represent the error on this average.

$$\tan\alpha = \frac{G_y}{G_x}$$

The result obtained for R_0 is very sensitive to the adopted value of $W_\odot$, as one obtains $R_0 = 45 \pm 99$ pc when decreasing $W_\odot$ by only 1 km s^{-1}. The values obtained for $|G|$ and α are nevertheless practically independent of this choice. The gradient in W can be appreciated in Figure 1, where its average over 100 pc-wide bins is plotted as a function of the distance to the axis of vertical oscillation. To test the real existence of such a gradient and its orientation, the system of Eqs. (2) has been solved repeatedly by adding each time a random component compressed between -10 km s^{-1} and 10 km s^{-1} to the W component of each stellar velocity, and by removing from the sample stars with $W > 10$ km s^{-1} or $W < -30$ km s^{-1}, so as to ensure that the results obtained are not a consequence of a spurious effect or of stars with a highly deviant behaviour. Results within or near the above intervals have been consistently obtained every time for $|G|$ and α. It should be noted that at $b = 0^\circ$ (which is roughly the case for most of the stars in our sample) Eq. (2) can also be written as $\mu_b = k(G_x \sin l - G_y \cos l) + |G|R_0\pi''$, where μ_b is the proper motion in galactic latitude, k is a conversion factor, and π'' is the trigonometric parallax. Since μ_b can be determined directly from *Hipparcos* proper motions, the determination of G_x and G_y is practically insensitive to systematic effects introduced by random errors in the parallaxes of the stars in the sample.

The meaning of the results found here will be better interpreted in the framework of the models for the internal kinematics of the Belt, and their discussion is therefore deferred to Section 4. For the time being, it should be noted that the orientation of the axis of vertical oscillation is markedly different from the direction of the nodal line where the Gould Belt intersects the galactic plane, which runs approximately along the $105° - 285°$ direction (Comerón et al. 1994, Torra et al. 1999). As will be seen, the offset between both directions has important implications on the internal dynamics of the Gould Belt. On the other hand, it will be shown as well that the rather low value of $|G|$ implies that the Gould Belt plane is near its maximum tilt at present. This feature was also noted by Frogel & Stothers 1977, on the basis of the absence of any significant gradient of the W component in the direction perpendicular to the galactic plane.

3. Kinematics

In the epicyclic approximation used to describe the orbits of stars moving in a separable potential, the equations of motion are usually written in a rotating cartesian reference frame whose axes are respectively directed towards the galactic center, the direction of galactic rotation, and the North galactic pole. The equations of motion can then be written as

$$x(t) = X_1 + \mathcal{C}\cos(\kappa t + \phi) \tag{4a}$$

$$y(t) = Y_1 + 2A_cX_1t + \frac{2\omega\mathcal{C}}{\kappa}\sin(\kappa t + \phi) \tag{4b}$$

$$z(t) = \mathcal{D}\cos(\nu t + \psi) \tag{4c}$$

where I use a notation similar to that of Comerón et al. 1997[1], adding equation (4c) to describe the motion perpendicular to the galactic plane. The angular velocity of an object in a circular orbit around the galactic center at the position momentarily occupied by the Sun is ω which, by definition, is also the angular velocity of the chosen reference frame with respect to an inertial one. A_c is the usual Oort constant for the case of pure galactic differential rotation, κ is the epicyclic frequency in the galactic plane, and ν is the oscillation frequency perpendicular to the galactic plane for orbits whose amplitude is well below the scale height of gravitating matter in the galactic disk. X_1 and $Y_1 + 2A_cX_1t$ describe the position of the guiding center of the epicyclic orbit, $\mathcal{C}$ is the amplitude of the epicycle in the galactocentric direction, $\mathcal{D}$ is the amplitude of the vertical oscillation, and ϕ and ψ define the position of a star in its orbit at an instant t.

[1] I use here ω to denote the angular velocity of circular galactic rotation, motivated by the later use of Ω to refer to the longitude of the ascending node in the present paper. The subindex "c" has been added to A to indicate the value of the latter in the case of pure galactic differential rotation. The amplitudes $\mathcal{C}$, $\mathcal{D}$ are written in that way to distinguish $\mathcal{C}$ from one of the Oort constants appearing later.

Developing the arguments of the trigonometric functions in Eqs. (4), and using the values of the coordinates and velocities at the initial instant $t = 0$, it is easy to show that Eqs. (4) can be written in the following compact form:

$$\boldsymbol{x} = \mathsf{S}\ \boldsymbol{x}_0 + \mathsf{T}\ \dot{\boldsymbol{x}}_0 \tag{5}$$

where $\boldsymbol{x} = (x(t), y(t), z(t))$, $\boldsymbol{x}_0 = (x(0), y(0), z(0))$, $\dot{\boldsymbol{x}}_0 = (\dot{x}(0), \dot{y}(0), \dot{z}(0))$. The elements of the matrices S, T are:

$$\mathsf{S} = \begin{pmatrix} \dfrac{\omega - A_c\cos\kappa t}{\omega - A_c} & 0 & 0 \\ \dfrac{2A_c\omega}{\omega - A_c}(t - \dfrac{\sin\kappa t}{\kappa}) & 1 & 0 \\ 0 & 0 & \cos\nu t \end{pmatrix}$$

$$\mathsf{T} = \begin{pmatrix} \dfrac{\sin\kappa t}{\kappa} & \dfrac{\cos\kappa t - 1}{2(\omega - A_c)} & 0 \\ \dfrac{2\omega}{\kappa^2}(1 - \cos\kappa t) & \dfrac{1}{\omega - A_c}(\dfrac{\omega\sin\kappa t}{\kappa} - A_ct) & 0 \\ 0 & 0 & \dfrac{\sin\nu t}{\nu} \end{pmatrix}$$

If the stars had a common origin so that the present age of the system is t, then the initial positions are related to the present ones and to the initial velocity pattern by

$$\boldsymbol{x}_0 = \mathsf{S}^{-1}(\boldsymbol{x} - \mathsf{T}\ \dot{\boldsymbol{x}}_0) \tag{6}$$

On the other hand, if the initial positions of stars were distributed on a plane tilted with respect to the galactic plane, then their initial positions fulfilled the relationship

$$\mathcal{P}_0(\boldsymbol{x}_0 - \boldsymbol{x}_{r0}) = 0 \tag{7}$$

where $\mathcal{P}_0$ is the vector perpendicular to the plane and $\boldsymbol{x}_{r0}$ defines the location of the plane with respect to the origin of coordinates. Replacing Eq. (6) in Eq. (7),

$$\mathcal{P}_0\left[\mathsf{S}^{-1}(\boldsymbol{x} - \mathsf{T}\ \dot{\boldsymbol{x}}_0) - \boldsymbol{x}_{r0}\right] = 0 \tag{8}$$

It is then possible to show that, if the pattern of initial velocities can be expressed as a linear function of the initial coordinates of the stars, then the tilted plane remains as a tilted plane as the positions of its stars evolve with time under the influence of the galactic potential. Let the linear combination be expressed in a general form as

$$\dot{\boldsymbol{x}}_0 = \mathsf{U}(\boldsymbol{x}_0 - \boldsymbol{x}_c) + \dot{\boldsymbol{x}}_c \tag{9}$$

Using Eq. (6), one obtains after some algebra:

$$\dot{\boldsymbol{x}}_0 = (\mathsf{U}\mathsf{S}^{-1}\mathsf{T} + \mathsf{I})^{-1}\left[\mathsf{U}(\mathsf{S}^{-1}\boldsymbol{x} - \boldsymbol{x}_c) + \dot{\boldsymbol{x}}_c\right] \tag{10}$$

where I is the identity matrix. Replacing this in Eq. (8),

$$\mathcal{P}_0\left[\mathsf{S}^{-1}\boldsymbol{x} - \mathsf{S}^{-1}\mathsf{T}(\mathsf{U}\mathsf{S}^{-1}\mathsf{T} + \mathsf{I})^{-1}\left[\mathsf{U}(\mathsf{S}^{-1}\boldsymbol{x} - \boldsymbol{x}_c) + \dot{\boldsymbol{x}}_c\right] - \boldsymbol{x}_{r0}\right] = 0 \tag{11}$$

This can be expressed simply as

$$\mathcal{P}(\boldsymbol{x} - \boldsymbol{x}_r) = 0 \tag{12}$$

which is again the equation of a plane, whose perpendicular vector is now

$$\mathcal{P} = \mathcal{P}_0[\mathsf{S}^{-1} - \mathsf{S}^{-1}\mathsf{T}(\mathsf{U}\mathsf{S}^{-1}\mathsf{T} + \mathsf{I})^{-1}\mathsf{U}\mathsf{S}^{-1}] \tag{13}$$

and the present location of the plane is defined by

$$\mathcal{P}\boldsymbol{x}_r = \mathcal{P}_0[\mathsf{S}^{-1}\mathsf{T}(\mathsf{U}\mathsf{S}^{-1}\mathsf{T} + \mathsf{I})^{-1}(\mathsf{U}\boldsymbol{x}_c - \dot{\boldsymbol{x}}_c) - \boldsymbol{x}_{r0}] \tag{14}$$

Given the geometry of stellar initial positions and velocities, it may be more convenient to write them in a reference frame whose axes are aligned parallel or perpendicular to the plane, and whose origin is chosen so as to simplify the expression of the initial law of motion. In such a reference frame, in which the position vector is denoted by ξ, the initial law of motion can be written as

$$\dot{\xi}_0 = \mathsf{M}\xi_0 \tag{15}$$

where the relation between $\boldsymbol{x}_0$ and ξ_0 is

$$\boldsymbol{x}_0 = \Omega_0 \mathsf{i}_0 \xi_0 + \boldsymbol{x}_c \tag{16}$$

The rotation of axes is explicitly decomposed as the product of two rotations whose matrices are

$$\Omega_0 = \begin{pmatrix} \cos\Omega_0 & -\sin\Omega_0 & 0 \\ \sin\Omega_0 & \cos\Omega_0 & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

$$\mathsf{i}_0 = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos i_0 & -\sin i_0 \\ 0 & \sin i_0 & \cos i_0 \end{pmatrix}$$

The initial inclination of the plane with respect to the galactic plane is i_0, and the longitude of the nodal line defined by the intersection of both planes is Ω_0. An expression analogous to Eq. (16) can be written for the velocity:

$$\dot{\boldsymbol{x}}_0 = \Omega_0 \mathsf{i}_0 \dot{\xi}_0 + \dot{\boldsymbol{x}}_c \tag{17}$$

The initial law of motion expressed in the usual epicyclic motion base is thus

$$\dot{\boldsymbol{x}}_0 = \Omega_0 \mathsf{i}_0 \mathsf{M} \mathsf{i}_0^{-1} \Omega_0^{-1}(\boldsymbol{x}_0 - \boldsymbol{x}_c) + \dot{\boldsymbol{x}}_c \tag{18}$$

which gives the expression of U

$$\mathsf{U} = \Omega_0 \mathsf{i}_0 \mathsf{M} \mathsf{i}_0^{-1} \Omega_0^{-1} \tag{19}$$

The time evolution of the nodal line and the inclination are thus given by that of the vector $\mathcal{P}$, whose components are

$$\mathcal{P} \propto (\sin\Omega \sin i, -\cos\Omega \sin i, \cos i) \tag{20}$$

This derivation allows a rather straightforward connection between the matrix U and the local values of the Oort constants, which can be measured from the observations. Developing Eq. (5) with the use of Eq. (9), one obtains:

$$\boldsymbol{x} = (\mathsf{S} + \mathsf{T}\mathsf{U})\boldsymbol{x}_0 - \mathsf{T}(\mathsf{U}\boldsymbol{x}_c - \dot{\boldsymbol{x}}_c) \tag{21}$$

Taking the time derivative of Eq. (21),

$$\dot{\boldsymbol{x}} = (\dot{\mathsf{S}} + \dot{\mathsf{T}}\mathsf{U})\boldsymbol{x}_0 - \dot{\mathsf{T}}(\mathsf{U}\boldsymbol{x}_c - \dot{\boldsymbol{x}}_c) \tag{22}$$

Using Eq. (21) to isolate $\boldsymbol{x}_0$, and replacing it in Eq. (22), one obtains

$$\dot{\boldsymbol{x}} = (\dot{\mathsf{S}} + \dot{\mathsf{T}}\mathsf{U})(\mathsf{S} + \mathsf{T}\mathsf{U})^{-1}[\boldsymbol{x} + \mathsf{T}(\mathsf{U}\boldsymbol{x}_c - \dot{\boldsymbol{x}}_c)] - \dot{\mathsf{T}}(\mathsf{U}\boldsymbol{x}_c - \dot{\boldsymbol{x}}_c) \tag{23}$$

Taking spatial derivatives now, one obtains

$$\mathsf{Q} = (\dot{\mathsf{S}} + \dot{\mathsf{T}}\mathsf{U})(\mathsf{S} + \mathsf{T}\mathsf{U})^{-1} \tag{24}$$

where the elements of Q, Q_{ij}, are

$$Q_{ij} = \frac{\partial \dot{x}_i}{\partial x_j} \tag{25}$$

It should be noted that Eq. (24) is valid for any system of stars for which the epicyclic approximation applies, and whose initial positions and velocities are related by Eq. (9). The additional condition (7), implying that the stars are distributed in a plane, has not been used in deriving Eq. (24). This condition must be implicitly included in the expression of the spatial derivatives that will be actually used here in the calculation of the Oort constants, namely:

$$\left(\frac{\partial \dot{x}_i}{\partial x_j}\right)_p = \frac{\partial \dot{x}_i}{\partial x_j} - \frac{\partial \dot{x}_i}{\partial z}\frac{\mathcal{P}_j}{\mathcal{P}_3} \tag{26}$$

where the p subindex denotes the derivatives measured on the plane, and x_j is either x or y. Using these definitions, the Oort constants become

$$A = \frac{1}{2}(Q_{12} + Q_{21} - Q_{13}\frac{\mathcal{P}_2}{\mathcal{P}_3} - Q_{23}\frac{\mathcal{P}_1}{\mathcal{P}_3}) \tag{27a}$$

$$B = \frac{1}{2}(Q_{21} - Q_{12} - Q_{23}\frac{\mathcal{P}_1}{\mathcal{P}_3} + Q_{13}\frac{\mathcal{P}_2}{\mathcal{P}_3}) - \omega \tag{27b}$$

$$C = \frac{1}{2}(Q_{11} - Q_{22} - Q_{13}\frac{\mathcal{P}_1}{\mathcal{P}_3} + Q_{23}\frac{\mathcal{P}_2}{\mathcal{P}_3}) \tag{27c}$$

$$K = \frac{1}{2}(Q_{11} + Q_{22} - Q_{13}\frac{\mathcal{P}_1}{\mathcal{P}_3} - Q_{23}\frac{\mathcal{P}_2}{\mathcal{P}_3}) \tag{27d}$$

to which one can add the derivatives involving the velocity component perpendicular to the galactic plane, giving the components of the axis of vertical oscillation (see Eq. (3)):

$$G_x = Q_{32} - Q_{33}\frac{\mathcal{P}_2}{\mathcal{P}_3} \tag{28a}$$

$$G_y = -Q_{31} + Q_{33}\frac{\mathcal{P}_1}{\mathcal{P}_3} \tag{28b}$$

4. Initial patterns of motion

Undoubtedly, an important reason why no clear interpretation on the kinematical structure of the Gould Belt has emerged yet is that, whatever the initial pattern of velocities may have been at the time of its formation, it must have been severely distorted under the effects of galactic differential rotation during its lifetime. In principle, it should be possible to use the presently observed space velocities of the stars and their ages, together with a model of the galactic potential, to trace their orbits back in time and find both their initial positions and velocities. In practice, this would require a knowledge of velocities, distances, and ages much more accurate than is available at present in order to reach any reliable conclusions.

A different way to approach this problem consists of proposing different initial kinematical patterns and space distributions for the stars of the Gould Belt, and following their evolution with time until the best agreement with the present observations is reached. In case that a satisfactory solution cannot be found for any possible age of the Belt, the model is then discarded. This is the approach followed by Lindblad 1980, and extended by Westin 1985, to evaluate the suitability of models based on a radial expansion from a small volume or on the gravitational perturbation produced by a spiral arm to reproduce the observed values of the Oort constants. They concluded that none of those models provided an acceptable fit to the available observational material. Comerón et al. 1994 suggested an expansion from a line, rather than a point, as a possible way to achieve a better fit to the Oort constants derived from their data. Recently, Palouš 1998 has presented the result of N-body numerical simulations suggesting that the dissolution of an unbound rotating system of stars with an age of 3×10^7 years is the most favoured model in explaining the observed values of the Oort constants. Such an age is consistent with that derived from the individual ages of its component stars.

The development presented in Section 3 is well suited to the exploration of different kinematical models for several reasons. First, its predictions include the orientation of the Belt and the characteristics of the vertical motion, in addition to the Oort constants, as a function of time. Secondly, the development being fully analytical, it is easy to explore a wide range of parameters when trying to obtain a best fit, and to ensure that some models can be really discarded for any set of initial parameters. A possible drawback is the basic assumption that the initial patterns of motion have the generic form given by Eq. (9), what in principle is a very restrictive condition. However, the fact that such patterns are able to maintain the arrangement of stars on a tilted plane with time, and that this is indeed an observed feature of the Gould Belt, suggests that it should be possible (at least as a first approximation) to describe the initial pattern of motions of the Gould Belt in such a form.

The time evolution of the orientation of the Belt and of the Oort constants are described in the next Subsections for different possible initial patterns of motion. The main aspect of interest here is in the early phases of this evolution, this is, in ages of a few times 10^7 years which are consistent with the observations. For illustrative purposes, I extend the calculations to 3×10^8 years, which covers the first resonances with the epicyclic and galactic rotation periods and their consequences on the quantities whose evolution is studied here. Such an extension may be in principle relevant to the study of other, older Gould Belt-like structures which may be eventually discovered. However, the study of such structures would be hampered with increasing age as their more massive and brightest members end up their lives, and the less massive ones dilute in phase space due to differential rotation and to the dynamical heating mechanisms operating in the galactic disk.

The evolution of the plane orientation and the Oort constants are in general sensitive to the chosen initial parameters. For this reason, I restrict the discussion to the values that reproduce the present orientation of the Gould Belt ($\Omega = 285°$, $i = 20°$; see Section 2) and the small value of $G = |\boldsymbol{G}|$, which places the Gould Belt near its peak inclination at present. In general, it is always possible to find a set of initial parameters fulfilling these constraints for an age of the Belt compatible with the observational estimates. The consistency with these constraints thus sets rather narrow limits on the possible age of the Belt, which depend on the model adopted. As a convention, the inclination is defined here as a positive quantity, and Ω as the galactic longitude of the ascending node of the Gould Belt with respect to the galactic plane, so that the crossing of the galactic plane by the Gould Belt results in a change of 180° in Ω, rather than a reversal in the sign of i. In this way, $\Omega = 90°$ means that the Gould Belt reaches its largest distance to the galactic plane in the direction to the galactic anticenter, while $\Omega = 270°$ implies that it does so in the direction to the galactic center, and $\Omega = 0°$ places the direction of maximum inclination in the direction of the galactic rotation. For the sake of simplicity, and in consistency with the observations, I will consider $x_c = 0$, $\dot{x}_c = 0$. As can be seen from Eq. (24), the Oort constants are not affected by this choice.

The values adopted for the galactic constants A_c and κ appearing in the matrices S and T are those corresponding to a flat rotation curve at the position of the Sun with a circular angular speed of rotation $\omega = 25.9$ km s^{-1} kpc^{-1} (Kerr & Lynden-Bell 1986), namely $A_c = \frac{1}{2}\omega = 12.9$ km s^{-1} kpc^{-1} and $\kappa = 36.0$ km s^{-1} kpc^{-1}. The vertical oscillation frequency is taken to be $\nu = 99$ km s^{-1} kpc^{-1}, corresponding to a vertical oscillation period of 6.2×10^7 years (Binney & Tremaine 1987).

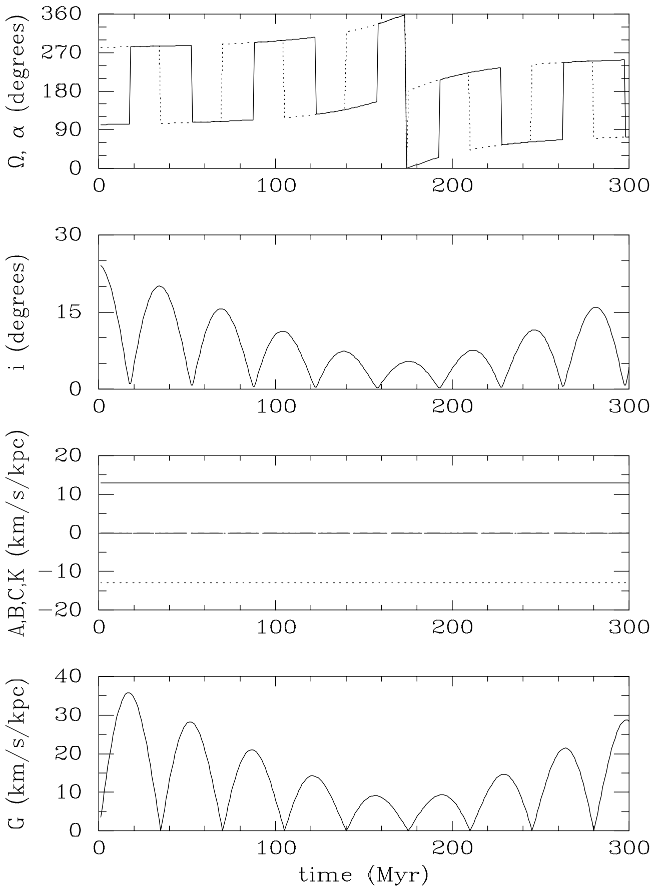

Fig. 2. The evolution of the nodal line Ω, the axis of vertical oscillation α, the inclination i, the Oort constants A, B, C, K, and the instantaneous angular velocity of oscillation G in the case in which the stars of the Gould Belt follow circular orbits around the galactic center while oscillating around the galactic plane. In the upper panel, the solid curve represents the direction of the nodal line, and the dashed curve the direction of the axis of vertical oscillation. The Oort constants are identified by the solid line (A), the dotted line (B), the dashed line (C), and the dot-dashed line (K). Note that $C = K = 0$ in the present case, so both curves overlap. The stars in the plane are assumed to form simultaneously with a zero vertical motion; the present orientation and peak inclination are obtained with the initial values $\Omega_0 = 102°2$, $i_0 = 24°2$, at an age of 3.4×10^7 years.

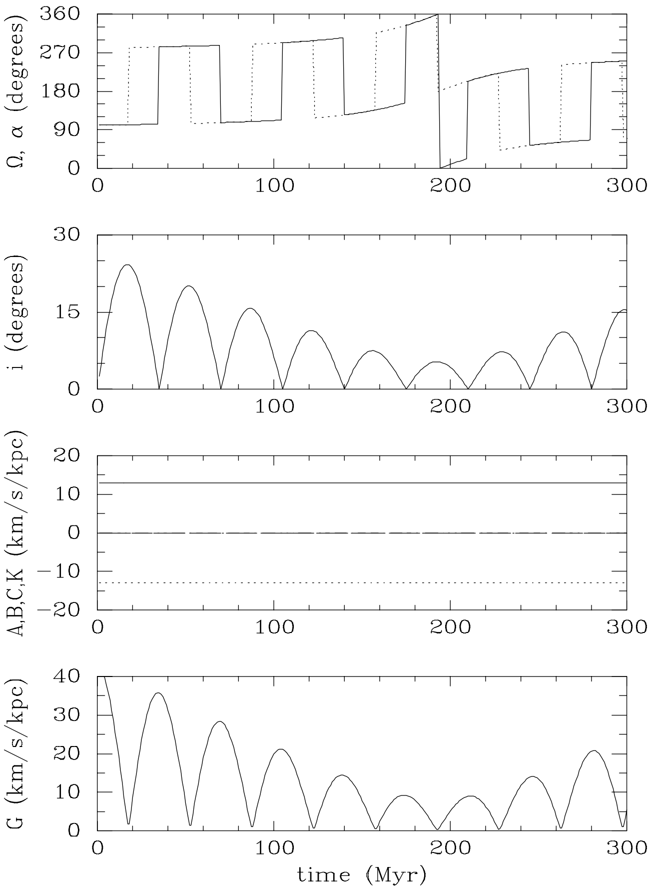

Fig. 3. Same as Figure 2, but now assuming that the stars are formed in the galactic plane with a nonzero vertical motion. The value of k in Eq. (28) is set to 43.2 km s^{-1} kpc^{-1} to obtain a maximum inclination of 20° at 5.2×10^7 years. The initial orientation in this case is $\Omega_0 = 101°1$, $i_0 = 0°$.

4.1. Circular motions

The simplest case that can be considered, and that will be used here as a reference, is that of a plane whose stars follow circular orbits around the galactic center when their positions are projected on the galactic plane. In the epicyclic reference frame, the equations of motion are described by Eqs. (4) with $\mathcal{C} = 0$, and one obtains for U:

$$\mathsf{U} = \begin{pmatrix} 0 & 0 & 0 \\ 2A_c & 0 & 0 \\ -k\sin\Omega_0 & k\cos\Omega_0 & 0 \end{pmatrix} \tag{29}$$

where the possibility of a nonzero vertical initial velocity is taken into account by the terms in the last row of Eq. (29). This includes also as a particular case one in which the star-forming matter of the Gould Belt is suddenly knocked away from the galactic plane towards opposite directions ($i_0 = 0$, $k \neq 0$).

Figure 2 shows the time evolution of the position of the nodal line Ω, the direction of the axis of vertical oscillation α, the inclination i, the value of the Oort constants A, B, C, K, and the instantaneous angular velocity of oscillation G. The values of Ω and α are their galactic longitudes at the corresponding time, i.e., they are expressed in the rotating reference frame. The evolution of the orientation can be described fairly simply: starting from the chosen initial position, the direction of the nodal line rotates in the sense of increasing galactic longitudes, assymptotically tending to align itself with the direction of galactic rotation, as a consequence of the "stretching" of the plane produced by galactic rotation. A point of the nodal line at the initial position (x_0, y_0) will have moved, following the galactic circular rotation, to $(x_0, y_0 + 2A_c x_0 t)$ after a time t, and the longitude of the nodal line will thus be given (neglecting the possible 180° difference due to the actual inclination) by $\tan\Omega = y/x = (y_0 + 2A_c x_0 t)/x_0$, which increases indefinitely with time. The axis of vertical oscillation is coincident with the nodal line, but its 180° reversals take place at the times when the vertical motions of stars change signs, rather than at the galactic plane crossings as is the case for the nodal line.

The evolution of the inclination is also easy to understand qualitatively, being dominated by the vertical oscillation of the stars around the galactic plane. The initial decrease of the amplitude of the inclination is due to the stretching of the plane as the nodal line approaches the galactocentric direction. Once the nodal line crosses it, the plane continues to stretch, but a projection effect makes the inclination amplitude grow again, and at sufficiently large times (several times larger than the timespan shown in Figure 2) it actually tends to 90°. The projection effect may be visualized as follows: let us assume, when $\Omega = 0°$, a star lying at the coordinates (x, y, z), so that the distance to the nodal line is y and the inclination of the plane is simply $\tan i = z/y$. As the nodal line rotates (i.e., as Ω approaches the $90° \rightarrow 270°$ direction), the distance d of the star to the nodal line decreases as $d = y\cos\Omega$, so that the inclination amplitude grows as $\tan i_{max} = z_{max}/d$, with the vertical amplitude of the oscillation, z_{max}, being constant.

Since the motions of the stars as projected on the galactic plane are circular around the galactic center in the present case, the Oort constants have the values $A = A_c$, $B = A_c - \omega$, $C = K = 0$ characteristic of such motion. The evolution of $|G|$ is similar to that of $|i|$, but anticorrelated with it, as expected from the stars reaching their peak vertical velocity when they cross the galactic plane. The projection effect discussed in the previous paragraph applies to the gradients of the vertical velocity as well, what causes the amplitude of the oscillation in G to vary in a similar way to that of i.

The results remain essentially unchanged if the stars are assumed to be born in the galactic plane and expelled from there in a coherent way, with vertical velocities proportional to the distance to the nodal line. This is shown in Figure 3, which displays the same behaviour as Figure 2, the differences being due to the somewhat different initial parameters that are necessary to match the constraints set by the presently observed orientation and state of vertical motion of the Belt.

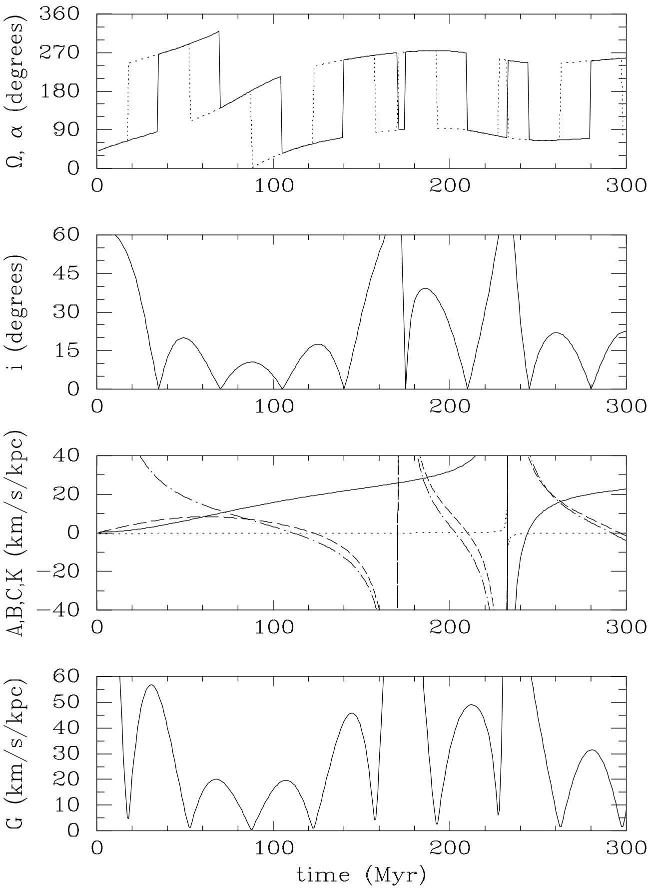

Fig. 4. The evolution of the nodal line Ω, the axis of vertical oscillation α, the inclination i, the Oort constants A, B, C, K, and the instantaneous angular velocity of oscillation G in the case in which the stars of the Gould Belt are born simultaneously and expand initially from a negligibly small volume with random velocities ($\tau_0 \rightarrow 0$ in Eq. (30)). In the upper panel, the solid curve represents the direction of the nodal line, and the dashed curve the direction of the axis of vertical oscillation. The Oort constants are identified by the solid line (A), the dotted line (B), the dashed line (C), and the dot-dashed line (K). The present orientation and peak inclination are obtained with the initial values $\Omega_0 = 40°7$, $i_0 = 63°5$, at an age of 4.9×10^7 years.

4.2. Radial expansion

Let us assume now that the stars in the Gould Belt were born simultaneously in a volume much smaller than the one they occupy at present, with their initial motions contained in a plane and directed radially away from the center of such volume. This is one of the most widely considered kinematical models for the Gould Belt, motivated by the long-recognized expansion term in the velocities of nearby young stars. The early work of Blaauw 1952 describing the expansion of an unbound group of stars moving in the galactic potential was extended by Lesh 1968, Lindblad 1980, and Westin 1985. Lindblad et al. 1973 and Olano 1982 developed the models to account for the observed radial velocities of the gas associated to the Belt.

Let us assume an initial velocity modulus of the stars proportional to the distance to the center. At very early times, it is possible to define an expansion age τ_0 such that the pattern of motions can be described, using the ξ_0 system defined above, as follows:

$$\mathsf{M} = \frac{1}{\tau_0}\begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 0 \end{pmatrix} \qquad (30)$$

If the initial volume is negligible, then $\tau_0 \to 0$, and the pattern described by Eq. (30) is equivalent to that of a system of stars expelled from a single point with random velocities. The evolution of the orientation of the plane is then as given in Figure 4. The main characteristic is the fast decrease of the amplitude of the tilt with time at early ages, as a consequence of the expansion of its stars away from the center while maintaining constant the amplitude of their vertical motions. An important feature of this model is the need for a large initial tilt, $i = 63^\circ 5$, to still obtain a maximum tilt of 20° at the age of 4.9×10^7 years, after the first galactic plane crossing.

The initial expansion along the plane from a very small volume causes a large initial gradient in the vertical component of the velocity resulting in a large value of G, which rapidly decreases as the distance of the stars to the center of the expansion grows. Afterwards, the evolution of G and i are approximately anticorrelated like in the case of circular motions, although the expansion of the system causes a small lag between the peak in i and the minimum in G: since the distance to the center of expansion increases, the inclination can start decreasing while the stars are still moving away from the galactic plane. A common feature to the expansion models, including those to be considered in the next Section, is the predicted permanent alignment between the nodal line and the vertical oscillation axis.

The evolution of the Oort constants plotted in Figure 4 reproduces the results of Lindblad 1980, giving low values at early times for all the Oort constants (including a permanent null value of B) with the exception of K. Singularities in some Oort constants and in the orientation of the plane appear around the times of the epicyclic period and the galactic rotation period, due to the alignment of the stars of the plane along a single line, what gives infinite values for some spatial derivatives of some velocity components. This is a feature common to the evolution of all the models in which the stellar orbits projected on the galactic plane are not circular.

A similar, but less marked behaviour, is found when τ_0 is finite. This may be regarded as an approximation to the case in which the stars formed out of an extended molecular cloud become an unbound system shortly after their formation, as a consequence of the dispersal of the gas remaining in the system. Assuming that the stars located at the outskirts of the cloud expand initially with a velocity of 1 km s^{-1}, and that the star forming cloud had an initial radius of 50 pc, one obtains $\tau_0 \simeq 5 \times 10^7$ years. The evolution is given in Figure 5, and is nearly identical to that depicted in Figure 4 except for the existence of a negative value of B. The initial nonzero extent of the Belt allows to start with an inclination of its plane somewhat smaller than in the case $\tau_0 \to 0$ considered before, but still very considerable despite of the small expansion velocity at the outskirts of the cloud.

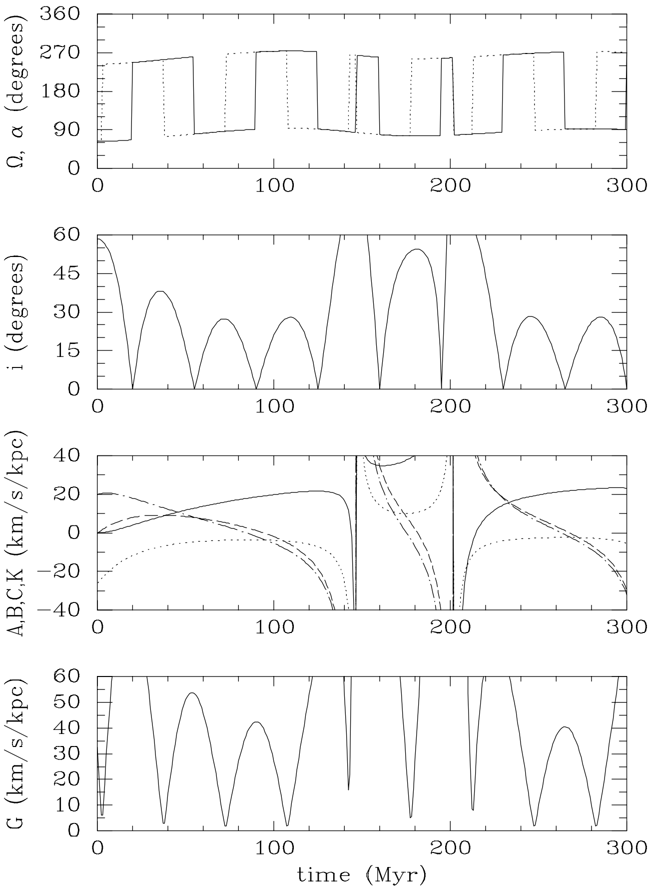

Fig. 5. The evolution of the nodal line Ω, the axis of vertical oscillation α, the inclination i, the Oort constants A, B, C, K, and the instantaneous angular velocity of oscillation G in the case in which the stars of the Gould Belt are born simultaneously over a circular region, expanding with initial velocities proportional to the distance to the center. The expansion age, which relates the size of the initial volume and the expansion rate, is taken to be 5×10^7 years, as explained in the text. In the upper panel, the solid curve represents the direction of the nodal line, and the dashed curve the direction of the axis of vertical oscillation. The Oort constants are identified by the solid line (A), the dotted line (B), the dashed line (C), and the dot-dashed line (K). The present orientation and peak inclination are obtained with the initial values $\Omega_0 = 63^\circ 0$, $i_0 = 58^\circ 4$, at an age of 4.1×10^7 years.

4.3. Expansion from a line

In this Secton I consider the case in which the initial expansion takes place along a preferential direction, rather than being isotropic as it has been assumed so far. Such an expansion pattern was proposed by Comerón et al. 1994 on the basis of the distribution of residual velocities of Gould Belt stars when a purely circular rotation is subtracted from the observed velocities. It was suggested in

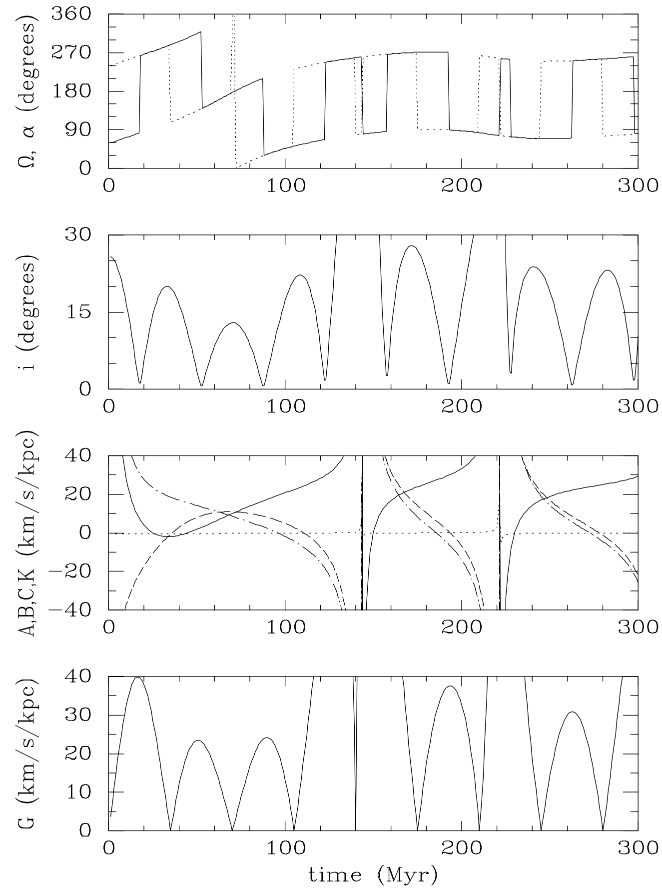

Fig. 6. The evolution of the nodal line Ω, the axis of vertical oscillation α, the inclination i, the Oort constants A, B, C, K, and the instantaneous angular velocity of oscillation G in the case in which the stars of the Gould Belt are born simultaneously on a very narrow strip, and expand initially with random velocities directed prependicular to it. The strip is assumed to coincide with the apsidal line, so that the initial expansion takes place parallel to the direction of the nodal line. In the upper panel, the solid curve represents the direction of the nodal line, and the dashed curve the direction of the axis of vertical oscillation. The Oort constants are identified by the solid line (A), the dotted line (B), the dashed line (C), and the dot-dashed line (K). The present orientation and peak inclination are obtained with the initial values $\Omega_0 = 58°3$, $i_0 = 25°9$, at an age of 3.3×10^7 years.

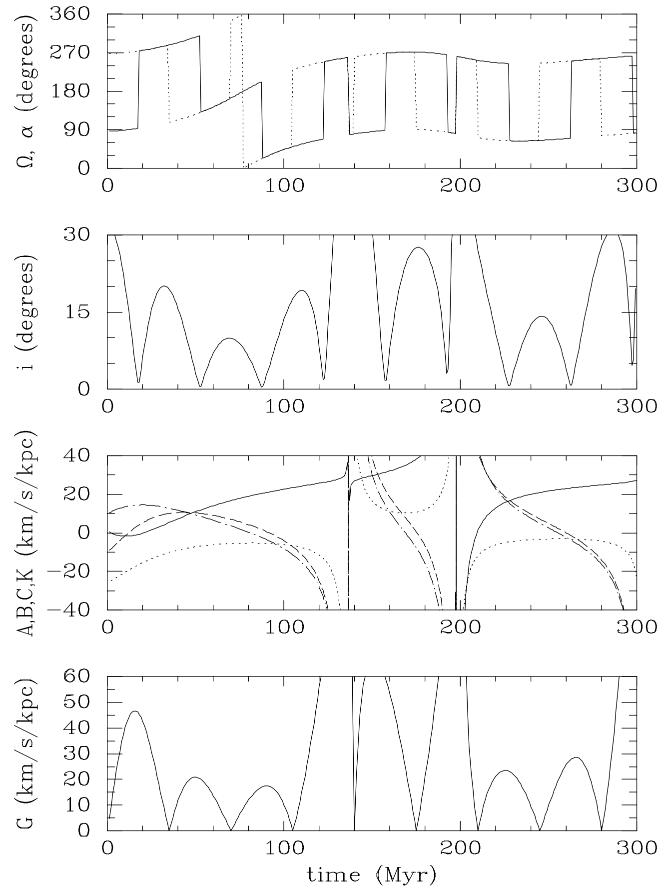

Fig. 7. The evolution of the nodal line Ω, the axis of vertical oscillation α, the inclination i, the Oort constants A, B, C, K, and the instantaneous angular velocity of oscillation G in the case in which the stars of the Gould Belt are born simultaneously and expand initially on a plane, with velocities that are parallel to the nodal line and proportional to their distance to it. The expansion age of the system is set to 5×10^7 years. In the upper panel, the solid curve represents the direction of the nodal line, and the dashed curve the direction of the axis of vertical oscillation. The Oort constants are identified by the solid line (A), the dotted line (B), the dashed line (C), and the dot-dashed line (K). The present orientation and peak inclination are obtained with the initial values $\Omega_0 = 87°3$, $i_0 = 32°0$, at an age of 3.4×10^7 years.

that paper that such a pattern may have arisen from the sudden compression of a gas layer precursor to the Gould Belt, threaded by a magnetic field aligned with the direction of galactic rotation. The subsequent expansion of the gas would have taken place preferentially along the magnetic field lines, and would be reflected now in the motions of the stars formed out of that gas. Rather than a radiant point marking the center of expansion, it is possible in this case to define a *radiant line* so that stars move initially away from it following trajectories perpendicular to it.

Assuming that the initial velocity of any given star has a modulus proportional to the distance to the radiant line, one obtains an initial expansion law that can be expressed in the general form (9), with

$$\mathsf{M} = \frac{1}{\tau_0} \begin{pmatrix} \cos^2\beta & \cos\beta\sin\beta & 0 \\ \cos\beta\sin\beta & \sin^2\beta & 0 \\ 0 & 0 & 0 \end{pmatrix} \qquad (31)$$

where β is the angle between the direction of expansion and that of the nodal line, and τ_0 is again the expansion age, now defined as the ratio between the initial distance of a star to the radiant line and its initial velocity. Two cases similar to those presented in Sect. 3.2 are shown in Figures

6 and 7, corresponding to $\tau_0 \to 0$ and $\tau_0 = 5 \times 10^7$ years. The angle β is taken to be 0° for both cases, implying that the radiant line is coincident with the apsidal line. The foundation for this choice lies in the physical motivation of this expansion law, as outlined above. The present position of the nodal line implies an initial position roughly aligned with the direction of galactic rotation, especially in the case $\tau_0 = 5 \times 10^7$ (Figures 6 and 7) and this is also the approximate orientation of the systemic component of the galactic magnetic field.

The $\tau_0 \to 0$ case has in common with the corresponding one in the radial expansion scenario the existence of a null constant B and the large positive initial K term, which decreases with time and eventually becomes negative when the epicyclic orbits reverse the initial expansion. However, the present case is characterized by large absolute values of A and C, unlike in the radial expansion case. The evolution of the orientation is similar between both cases, but now, due to the fact that the expansion takes place initially perpendicular to the direction of maximum inclination, the decrease in the amplitude of the inclination is much slower; this is, the initial tilt of the plane is not very different from the presently observed one, unlike in both of the radial expansion scenarios discussed before.

The early evolution when $\tau_0 = 5 \times 10^7$ years is qualitatively very similar to that of the radial expansion case with the same expansion age, with the largest differences, such as the initial $C < 0$ term, appearing only in the first 10^7 years of evolution.

As to the evolution of α and G, a behaviour similar to the radial expansion case (alignment of the axis of vertical oscillation with the nodal line, anticorrelation between i and G) is found for both cases, with the exception of the very early evolution in the case of G that now starts from a null value.

4.4. Rotation

The last model considered here concerns a tilted plane formed by stars which initially rotate with an angular velocity $\boldsymbol{w}$ around a perpendicular axis. The velocity $\boldsymbol{v}$ of a star on the plane is thus given by $\boldsymbol{v} = \boldsymbol{w} \times \boldsymbol{r}$, with $\boldsymbol{r}$ being the position vector of the star with respect to the center of rotation. This allows one to express the initial pattern of motion in terms of

$$\mathsf{M} = w \begin{pmatrix} 0 & -1 & 0 \\ 1 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix} \tag{32}$$

with w being the modulus of $\boldsymbol{w}$. To illustrate the resulting pattern of motions and choose a value best matching the actual observations, w is set to -6.5 km s^{-1} kpc^{-1}. The positive value of $\Omega + w$ corresponds to a prograde rotation, i.e., in the same direction as the galactic rotation (although with lower angular speed than the latter) in a fixed reference frame. The results are shown in Figure 8.

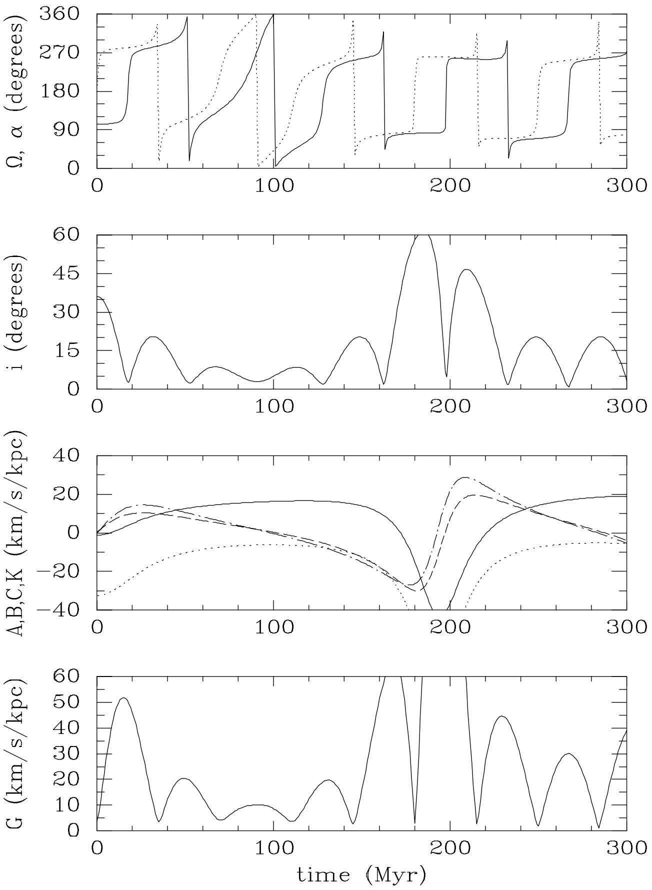

Fig. 8. The evolution of the nodal line Ω, the axis of vertical oscillation α, the inclination i, the Oort constants A, B, C, K, and the instantaneous angular velocity of oscillation G in the case in which the stars of the Gould Belt are born simultaneously in a plane which rotates like a solid body and move independently afterwards. The initial angular velocity of the plane is set to -6.5 km s^{-1} kpc^{-1}, i.e., the sense of rotation in the epicyclic reference frame has a direction opposite to that of the galactic rotation. In the upper panel, the solid curve represents the direction of the nodal line, and the dashed curve the direction of the axis of vertical oscillation. The Oort constants are identified by the solid line (A), the dotted line (B), the dashed line (C), and the dot-dashed line (K). The present orientation and peak inclination are obtained with the initial values $\Omega_0 = 103°3$, $i_0 = 36°0$, at an age of 3.4×10^7 years.

The evolution of the orientation of the plane, the Oort constants, and the parameters defining the oscillation of the stars around the galactic plane is clearly different from that in the cases studied so far. The most remarkable difference is the introduction of an offset between the nodal line and the axis of vertical oscillation, which is initially 90° as it would correspond to a rigid body rotation. The initial value of G is small but not zero, as the stars are moving across the plane and have their largest vertical velocity component at the nodal line. The offset between Ω and α is maintained with time, although its value varies as the initial circular rotation pattern is distorted by the differential galactic rotation. The combination of initial rigid body rotation and subsequent independent epicyclic orbits results in an anisotropic expanding motion, characterized by the positive values of C and K. The initial rotation also yields a large negative value of B (which is the rotational of the velocity field) at the earliest stages.

5. Discussion

Kinematical studies of the system of young stars in the solar neighbourhood over the last decades have revealed some clear features associated to the Gould Belt, which have been reinforced by the accurate picture of the stellar kinematics in the solar neighbourhood provided by *Hipparcos* (Lindblad et al. 1997, Palouš 1998, Torra et al. 1999). These features can be summarized as follows:

- The A constant has a value smaller than that corresponding to pure galactic differential rotation.
- The B constant is negative, and its absolute value is at least similar, and probably somewhat larger, than that corresponding to pure galactic differential rotation.
- The K constant, which should be null for pure galactic differential rotation, is clearly positive. The same seems to be true for the C constant.

To these features, one can add the ones related to the vertical motion that have been described in Section 2 of this paper:

- There is a small gradient of 6.5 ± 1.8 km s^{-1} kpc^{-1} in the vertical component of the velocity.
- The stars of the Gould Belt oscillate around the galactic plane around an axis that is misaligned by $\sim 52°$ with respect to the nodal line marking the intersection between the Gould Belt and the galactic plane.

These are the features, together with the observed orientation of the Gould Belt and its persistence over a time span of 3×10^7 years or more, that any kinematic model should aim at accounting for. Is any of the scenarios described in Section 4 favoured by these observed features?

Expansion models in which the stars of the Gould Belt formed in a small volume successfully account for the observed behaviour of the A, C, and K constants. Nevertheless, they seem to be excluded by the large negative value of B, as noted by Lindblad 1980 and Palouš 1998. Models that assume that the stars formed in a narrow strip and expand initially along a preferential direction also account for the values of A, C, and K, although they do so only after an early evolution characterized by large positive values of A and K, and a large negative value of C. However, the previous objection concerning B applies in this case too, as a permanent null value of B is also predicted in this scenario.

The main objection to those expansion models, namely their inability to reproduce a value of B significantly different from zero, weakens if the Gould Belt started its expansion from a plane that had already a considerable extent. In this case, the observed features in A, C, and K are still successfully reproduced, but now with a clearly negative value of B, in better agreement with the observations. As far as the Oort constants and the orientation of the Gould Belt are concerned, the predictions of both the model of radial expansion and the model of expansion along a line are essentially the same. However, none of the expansion models is able to account for the main feature discussed in this paper concerning the vertical motion of stars, namely the large offset between the axis of vertical oscillation and the nodal line. Moreover, radial expansion models require a large initial tilt of the plane of the Belt, as can be seen in Figures 4 and 5, and it is difficult to imagine a formation mechanism that could account for such a large value.

The rotation model is the only one among the models studied here that predicts the offset between the axis of vertical oscillation and the nodal line. Most interestingly, the choice of an initial rigid body rotation with $w = -6.5$ km s^{-1} kpc^{-1}, and of the initial orientation parameters of the Gould Belt, is able to produce a remarkably good fit, at least qualitatively, to *all* the features observed in the Gould Belt, including its present orientation, the peculiarities of the Oort constants, and the characteristics of its vertical motion, if the age of the Gould Belt is 3.4×10^7 years. The agreement can be appreciated by comparing the measured values of the different parameters with those predicted by the model at that age, given in Table 1. In such comparison, we have adopted the values of Table 4 of Torra 1999 for their sample of stars at a distance of less than 600 pc from the Sun and an age below 6×10^7 years. As to the results of Lindblad et al. 1997, the values listed correspond to their sample of 144 stars within the rectangular area limited by -450 pc $- y < -x < 600$ pc $- y$, -450 pc $+ y < -x < 990$ pc $+ y$. The differences between both sets of results may provide an idea of the subsisting uncertainties in the derived value of the Oort constants.

The dating of the Belt based on its kinematical behaviour at present is strongly constrained by the mild gradient observed in the vertical component of the velocity: a difference of only 5×10^6 years would result in $G > 10$ km s^{-1} kpc^{-1}, a value that would start conflicting with the observations. The accurate dating based on the small value of G is a common feature for all the models, but unfortunately different models place the age at which G is sufficiently small at different times. Therefore, it is not possible to use the observed value of G for a model-independent dating of the Gould Belt. Nevertheless, the fact that the pattern based on the evolution of a disk initially in rotation is by far the one providing the best fit to the data leads one to strongly favour 3.4×10^7 years as the true age of the Gould Belt. Remarkably, as can be seen from Figure 8, the direction of the axis of vertical oscillation changes rapidly with time when the Belt is near its greatest tilt with respect to the galactic plane. For this reason, even the large uncertainty in the value of α is a more stringent constraint on the present age of the Belt, as a difference of only 3×10^6 years brings the predicted value of α outside the range allowed by the observations. An age of 3.4×10^7 years is in good agreement with the one adopted by Palouš 1998, although the Keplerian rotation pattern proposed in that paper is different from the solid body rotation studied here. It should be noted that the non-linear dependence between positions and velocities implied by the Keplerian rotation pattern makes the formulism developed in Section 3 not applicable to that case, which is why such a pattern has not been considered in the present study. Moreover, an initially Keplerian rotation lacks the property of keeping the stars distributed on a plane as time passes.

The initial rotation of the Gould Belt system has important implications concerning possible hypotheses for its origin. The failure of pure expansion models in explaining basic features of the present day kinematical behaviour of the Belt rules out models invoking a very energetic event, or a chain of them, in a small volume as the cause for the velocities of the stars. This does not mean that such explosive events have not taken place at all: on the opposite, they must have been relatively frequent as the oldest most massive members of the Gould Belt have exploded as supernovae, or as the stellar winds from its O and B stars have injected large amounts of energy in their surroundings. Many features in the interstellar medium of the Gould Belt, such as the Local Bubble (Cox & Reynolds 1987, the Lindblad Ring of HI (Lindblad et al. 1973), or the shells around the Scorpius-Centaurus-Lupus association (de Geus 1992) testify to the importance of the past and present interaction of the Gould Belt stars with the interstellar medium. However, the mechanism that gave origin to these stars in the first place has most probably to be searched elsewhere.

A simplified, straightforward interpretation of the kinematical history of the Gould Belt may be to assume the existence of a giant, rotating molecular cloud that started to form stars about 3.4×10^7 years ago, becoming unbound in the process, probably because of the loss of the gas that was not employed in the formation of stars. Although such a scenario seems in principle plausible, it would require an initial tilt of the molecular cloud of $\simeq 36°$ with respect to the direction perpendicular to the galactic plane, whereas actual giant molecular clouds are seen to have their rotation axes well aligned with that direction (Blitz 1993).

An alternative model for the origin of the Gould Belt was proposed by Comerón & Torra 1992, 1994 based on the consequences of the impact of a high velocity cloud from the galactic halo on the galactic disk. The model was proposed mainly to account for the initial tilt of the Belt, which appeared as a natural consequence of an impact along a direction not perpendicular to the galactic disk. The rotation pattern of the resulting layer of dense shocked gas, where star formation would then proceed, could not be considered in the two-dimensional hydrodynamical simulations presented in those works. However, it is conceivable that some rotation of the resulting structure may well result as a consequence of the collision, due to the transfer of the angular momentum of the impinging cloud to the shocked layer. A detailed examination of this aspect of the collision is beyond the scope of this paper, and should be studied by means of fully three-dimensional hydrodynamical simulations, which should ultimately decide whether the observed kinematical patterns are compatible or not with this hypothesis.

6. Summary

The main results of the present work can be summarized as follows:

- There is a systematic gradient in the vertical component of the velocity of the stars belonging to the Gould Belt along the galactic plane, subtle but detectable in the *Hipparcos* astrometric data. Such a gradient amounts of 6.5 ± 1.8 km s^{-1} kpc^{-1}, a rather small value that suggests that the Gould Belt is at present near its maximum tilt.
- The pattern of such vertical motions implies an instantaneous axis of oscillation around the galactic plane oriented along a line forming an angle of $52° \pm 20°$ with the direction of the nodal line in which the Gould Belt intersects the galactic plane.
- The maintenance of the distribution of the Gould Belt stars on a plane for a time that is comparable to the vertical oscillation period around the galactic plane can be achieved if the initial pattern of motions has a linear dependence with their initial positions.
- Analytical expressions can be found for the evolution of the orientation of the Gould Belt, the properties of the vertical velocities of their stars, and the Oort constants as a function of time under the assumption of a linear dependence between the initial positions and velocities and the validity of the epicyclic approximation to galactic orbits.
- Such evolution has been considered for different cases, whose initial parameters have been chosen so as to fit the presently observed orientation of the Gould Belt and its nearly maximum tilt.
- Comparison between model results and measured parameters seem to rule out kinematical models of the Gould Belt in which the stars initially expand away either from a point or from a line.
- A model in which the stars of the Gould Belt are initially rotating around an axis perpendicular to the plane of the Belt, and then move independently following their epicyclic orbits, achieves the best match to the observations, simultaneosly fitting the orientation of the Gould Belt, the Oort constants A, B, C, and K, the gradient in the vertical component of the

Table 1. Comparison between observed characteristics of the Gould Belt and those predicted by the best fitting rotation model.

	observed		predicted
	(Torra et al. 1999)	(Lindblad et al. 1997)	
A (km s^{-1} kpc^{-1})	7.2 ± 0.9	-6.1 ± 4.1	9.5
B (km s^{-1} kpc^{-1})	-18.8 ± 0.9	-20.6 ± 5.2	-15.3
C (km s^{-1} kpc^{-1})	6.0 ± 1.0	2.9 ± 3.7	9.9
K (km s^{-1} kpc^{-1})	4.9 ± 1.0	11.0 ± 3.5	13.8
G (km s^{-1} kpc^{-1})	6.5 ± 1.8 (this work)		4.5
$\alpha(^\circ)$	337 ± 20 (this work)		337
age (yr)	$> 3 \times 10^7$		3.4×10^7

velocity, and the offset between the axis of vertical oscillation and the direction of the nodal line. Such a best fit implies an age of $(3.4 \pm 0.3) \times 10^7$ years for the Gould Belt.

– It seems unlikely, in view of actual observations of giant molecular clouds, that the formation of the Gould Belt can be simply explained by the dissolution of such a complex, due to the requirement of a significant misalignment between its rotation axis and the direction perpendicular to the galactic plane. The impact of a high velocity cloud with the galactic disk as the formation mechanism of the Belt may provide a more adequate explanation.

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