The Gould Belt, star formation, and the local interstellar medium

Isabelle A. Grenier

AIM, Service d’Astrophysique, CEA Saclay, 91191 Gif/Yvette, France

The history of the local medium, within a few hundred parsecs, is dominated by the evolution of the Gould Belt. The event that triggered this star-forming region and molded the gas distribution is still unknown. Its orientation and extent are reasonably well determined and its expansion matches the space and velocity distributions of many large HI and H$_2$ clouds within half a kiloparsec. The present rim coincides with most of the nearby OB associations, but their mean velocity does not seem to be related to the Belt expansion. The Belt age is uncertain by a factor of 2 because of the discrepancy found between the dynamical timescale (20 to 30 Myr) and the stellar ages (30 to 60 Myr). The stellar content is derived from kinematic studies for massive stars and from X-ray observations for young solar-mass ones. Whether star formation is active along the rim or spread over a larger fraction of the disc is debated. The Belt flatness and its tilt remain very difficult to interpret. Various scenarios involve the impact of a high-velocity cloud, a cascade of supernovae, the dissolution of a rotating system, or the braking of a supercloud entering the spiral arm. Because of the enhanced star formation, the Belt supernova rate over the past few million years has been 3 to 4 times larger than the local Galactic rate. The corresponding pulsars may be responsible for the population of unknown γ-ray sources associated with the Belt. The higher rate also implies an enhanced cosmic-ray production locally.

*Keywords*: Galaxy: solar neighbourhood, stars: early-type, stars: supernovae, stars: pulsars, ISM: kinematics and dynamics, Gamma rays: observations

1 The Belt geometry

Many stars have formed locally over the past few $10^7$ years in a surprisingly flat and inclined disc named the Gould Belt. The Sun happens to be crossing this structure. The asymmetry about the Galactic plane of the bright-star distribution was first pointed out by Sir John Herschel in 1847 and studied in 1874 by Benjamin A. Gould who determined the Belt orientation with respect to the Galactic plane. From the decomposition of the spatial distributions of the two intersecting discs in the *Hipparcos* data, Torra et al. found that 60 to 66% of the massive
stars with ages < 60 Myr and distances < 600 pc belong to the Belt. This fraction significantly
decreases to 42-44% for ages between 60 and 90 Myr. In terms of spectral types, 44% and 36% of
the O-B2.5 and O-B9.5 stars within 1 kpc are respectively linked to the Belt.

Significant changes in the Oort constants with stellar age within 600 pc reflect the Belt
kinematical influence. A nearly pure differential Galactic rotation is found for the old stars
(> 90 Myr) whereas the younger ones exhibit a marked decrease in A and a large negative B
value that suggests that the whole system is rotating. A positive K term, indicative of
expansion, is measured for stars younger than 30 Myr. These peculiarities remain after removing
the Sco-Cen and Ori OB1 associations from the sample, so stars outside these famous clusters
along the Belt rim participate to the unusual kinematics. The true velocity field may, however,
be more complex than the Oort constants would suggest. There is a systematic gradient in the
vertical velocities of the young stars along the Galactic plane and the ascending node longitude
for vertical oscillation is $337^\circ \pm 20^\circ$ instead of $296^\circ \pm 2^\circ$ for the Belt orientation.

Whereas the massive-star content has been extensively studied, less is known about the
low-mass star production. Young (30–80 Myr old) Lithium-rich solar-mass stars show up as
X-ray sources because of their active coronae. Even though the X-ray horizon is limited by
interstellar absorption to 150-300 pc for sources with luminosities of $(0.3 - 3) \times 10^{23}$ W typical of
young late-type stars, such stellar sources in the ROSAT All-Sky Survey nicely trace the Belt
in the sky.

The Gould Belt also contains interstellar clouds and has been early associated with an
expanding HI ring. The fact that dark clouds participate to the expansion was recognized
20 years later. Famous H$_2$ complexes, such as Orion, Ophiuchus, and Lupus, have long
been related to the Belt, but more recently mapped complexes, such as Aquila Rift, Cepheus,
Cassiopeia, Perseus, and Vela appear to be part of the expanding shell as well.

The present size of the gas shell was first estimated by comparing the radial velocities in the
Lindblad HI ring with the 2D expansion of a shock wave inside the Galactic plane, then with
the 3D expansion of a superbubble in a uniform medium. The dynamical evolution has been
revisited to allow 3D expansion in a non uniform medium and to compare with the location and
motion of all the nearby HI and H$_2$ clouds. An inclined cylindrical shock wave, with thickness
$H$, has been used. It sweeps momentum from the ambient medium where the gas density varies
with altitude above the Galactic plane according to the 90, 225, and 400 pc scale heights that
describe the HI layer, and to the 74 pc scale height of the local CO gas. Because of the
Galactic differential rotation, the circular section of the Belt rapidly evolves into an elliptical one
which precesses with time. The rim slightly takes an hourglass shape from its faster expansion in
the more rarefied medium at high altitude. The Belt further warps and falls back in the Galactic
gravitational potential. A density gradient with Galactocentric distance has little effect on the
evolution. The sequence that best matches the present location and longitude-latitude-velocity
distribution of all the nearby HI and CO clouds at $|b| > 5^\circ$ is displayed in Figure I. The current
Belt geometry is close to that depicted in the 30 Myr plot and the last plot illustrates the Belt
in 10-15 Myr from now.

The dimensions that best fit the cloud data are a height $H$ of 60 pc and semi-major axes
$a = 354 \pm 5$ pc and $b = 232 \pm 5$ pc, in good agreement with the sizes derived from the sole HI data
for the expansion of a 2D ring (360 x 210 pc) or a 3D superbubble in a uniform medium (341 x 267 pc).
The present inclination of $17.2^\circ \pm 0.3^\circ$ to the Galactic plane nicely compares with the
latest stellar estimates ($16^\circ - 22^\circ$ for massive stars younger than 60 Myr and $17.5^\circ - 18.3^\circ$
for O-B stars). The larger inclination of $27.5^\circ \pm 1^\circ$ indicated by the young solar-mass stars is
biased by the dominant Sco-Cen associations within the X-ray visibility horizon. The current
Belt centre is found at $104 \pm 4$ pc from the Sun, toward $l = 180^\circ \pm 2^\circ$, so the Sun is nearly
half way to the rim. The ascending node longitude $l_\Omega = 296.1^\circ \pm 2.0^\circ$ is $10^\circ$ higher than the
values obtained from the massive and young low-mass stars, possibly reflecting the time-lag.
Figure 1: The Gould Belt evolution as seen at different epochs after the outburst, in a plane perpendicular to the Galactic plane, centred on the Belt centre. The x axis points to the Galactic centre and the location of the Sun, nearly half way to the rim, is marked by an asterisk.
between stellar birth and the slowly precessing rim.

The Belt position and orientation differ from previous estimates because of the use of Hipparcos distance information and of major H$_2$ complexes in the second quadrant. They had not been firmly associated with the Belt before, but their direction, distance, and velocity appear to be quite consistent with the modelled Belt and with the HI Lindblad ring$^{35}$. In fact, nearly all the local H$_2$ complexes at $|b| > 5^\circ$ seem to participate to the shell, except the very nearby Taurus and R CrA clouds that are well inside the Belt, and the Chamaeleon clouds that belong to the Local Arm. Figure 2 shows the Belt trace across the sky with respect to the clouds.

2 Star-formation in the Belt

Figure 3 displays the current Belt geometry with respect to the OB associations, the positions of which are known from Hipparcos measurements$^{13}$. It nicely coincides with most of them, but for Col 121 and Cep OB2 that clearly lie outside the Belt, and for Lac OB1 that is too far on the wrong side of the Galactic plane. The total swept-up mass in the evolved cylindrical shell amounts to $2.4 \times 10^5$ M$_\odot$. The mass accumulated over the past few Myr varies with longitude and is lowest in the $35^\circ < l < 100^\circ$ and $-155^\circ < l < -110^\circ$ sectors which are indeed free of major cloud complexes and OB associations near the rim. There is, however, no convincing relation between the mean velocity field of the individual OB associations and the shell expansion$^{35}$.

The column-densities of active X-ray stars show a marked excess over the Galactic population that varies with longitude$^{25}$. It extends to the 300 pc visibility horizon in the $195^\circ - 285^\circ$ interval, and to the remote edge at 170 pc of the Sco-Cen associations in the $285^\circ - 15^\circ$ quadrant. It disappears in the $15^\circ - 105^\circ$ interval, and is hardly visible out to 150 pc in the $105^\circ - 195^\circ$ quadrant, once the very nearby Hyades and Pleiades groups are subtracted. The lack of active star formation within 50 pc is due to the Local Bubble. These distributions indicate that stellar formation is not only active along the Belt rim, but also 100 pc or so inward, i.e. over a significant, yet poorly constrained, radial extent. This picture is consistent with the spatial distribution of massive stars in the 3rd and 4th Galactic quadrants. Yet, as for the young X-ray stars, no ring-like enhancement is seen in the 1st and 2nd quadrants even though the OB star
visibility reaches quite beyond the Belt edge.

3 The Belt age and origin

The Belt dynamical ages agree reasonably well for the different types of outbursts (26.4 ± 0.4 Myr for the 3D cylindrical shock wave, 23 and 15.5 Myr for a superbubble expansion with and without internal pressure), but they are notably smaller than that derived from the stars (30-60 Myr for photometric ages, 30-80 Myr from X-ray activity, and 34 ± 3 Myr from stellar dynamics). The former are sensitive to the local gas density estimates, the latter to the separation of the Belt and Galactic populations and to the photometric age accuracy. To reduce this discrepancy, one may explore the influence of stellar rotation which can lower age estimates by 30 to 50%, particularly for high rotators such as OB stars.

The required initial kinetic energy of (1.0 ± 0.1) 10^{45} J in the 3D cylindrical shock wave is comparable, but 60% higher than that needed in the 2D model because of the extra work used to expand against the Galactic gravitational pull in the early phases. An equivalent energy of 6 10^{44} J is required for a superbubble expansion in a 3 times lower interstellar density, but against ambient pressure. This energy deposit is typical of multiple, rapidly succeeding supernovae inside a young stellar cluster. It is also typical of a hypernova powering a collimated γ-ray burst event, or of the potential energy of high-velocity clouds falling on the Galactic disc.

Preserving the structural coherence of the Belt stellar system over a large fraction of the vertical oscillation and expansion timescales is challenging. Pure expansion models cannot reproduce the stellar data. A system initially rotating as a solid body can remain flat and tilted in the Galactic gravitational potential if it is initially inclined. The angular momentum of the parent cloud would therefore not be perpendicular to the Galactic plane. The dissolution of such a self-gravitating rotating stellar system may explain the persistence of a flat expanding disc.

The Belt formation is still a puzzle. Its flatness and tilt remain very difficult to interpret.
Various scenarios involve the oblique impact of a high-velocity cloud on the Galactic disc or a cascade of supernova explosions (see for a review). The former naturally provides some inclination, the gas expansion, and it is consistent with the measured Oort constants. For instance, a 500 pc size, $10^{-2} \, M_\odot \, pc^{-3}$ cloud, falling at 100 km/s from the northern halo and from inside the solar circle, could have created the Gould Belt and the Monoceros R2 complex. Recent MHD simulations of an oblique impact, however, show that the hole punched in the Galactic disc and the lateral compression waves are strongly driven by the vertical density gradient, perpendicular to the Galactic plane, so getting a global inclination for the star-forming disc should be carefully investigated (J. Franco, private communication). On the other hand, the expanding shock wave from an explosive event or a rapid series of explosions can match the space and velocity distribution of the gas if an initial asymmetry provides a large inclination. Whether a $\gamma$-ray burst event would apply is being investigated. Whether subsequent supernovae or stellar winds inside the Belt keep powering its expansion at later stages is an open question. Injecting energy gradually would accelerate the Belt expansion and further increase the age discrepancy ($R \propto t^{3/4}$ instead of $R \propto t^{1/3}$ in a uniform medium), as well as reduce its eccentricity. The stellar orbits emerging from an expanding superbubble can reproduce the velocity field of the nearby O-B5.5 stars and of the HI Lindblad ring only if the stars from the Pleiades group are removed, suggesting that two independent events have formed the Pleiades and the Belt. Alternatively, a $2 \times 10^7 \, M_\odot$, 400 pc size supercloud has been proposed as the common precursor of the Sirius supercluster, the Gould Belt and the Local Arm. The braking and compression of the supercloud while entering a spiral arm would have produced the latter two while the stellar cluster, unaffected by friction, would have moved on, away from the gas system. The supercloud angular momentum being concentrated at large radii, the inner regions would collapse into a flattened disc, precursor of the Gould Belt, whereas the ejection of the outer parts into a super-ring would form a precursor of the Local Arm.

Whatever triggered the Belt and its expansion has so deeply influenced the local interstellar medium, in particular the pressure gradient, that the Local Bubble cavity, or rather the Local Chimney, has opened up to the halo along an axis perpendicular to the Belt disc. The chimney also notably opens toward more intermediate- and high-velocity clouds than other regions of the halo. It has been suggested that these clouds formed from material ejected by the initial Belt burst and they now fall back onto the Galactic disc. The lack of cold HI and the presence of intermediate-velocity clouds at high latitude in the 2nd quadrant could be the signature of an explosive event that took place 35 myr ago near the $\alpha$ Per association.

### 4 The Belt supernovae and cosmic rays

During its evolution, the Belt has produced massive stars, therefore supernovae, in excess of the local Galactic rate. Explosions should have lately occurred from the first generations of massive stars born in the Belt. In the next few tens of Myr, $340 \pm 30$ stars with masses $> 8 \, M_\odot$ will explode and their maximum lifetime implies a crude minimum rate $> 35$ collapses $Myr^{-1} \, kpc^{-2}$. In comparison, a Galactic rate of 20 events $Myr^{-1} \, kpc^{-2}$ is inferred at the solar circle from the distribution of stars in the Galaxy and from the average frequency of $2.5^{+0.8}_{-0.4}$ events per century for all types of supernovae in the Galaxy $\sim 85 \%$ of which arise from the core collapse of a massive star. This value reasonably agrees with the 29 progenitors $Myr^{-1} \, kpc^{-2}$ found with masses $> 8 \, M_\odot$ within 1 kpc from the Sun, in particular given the enhanced yield from the Belt inside this region. A rate can be inferred for the recent past from the current Belt stellar content as a function of mass, given the $\Gamma$ index of the initial mass spectrum ($dN/dM \propto M^{\Gamma-1}$), lifetime estimates for stars with solar metallicity, a constant birth rate for simplicity, a conservative mass threshold for collapse of $8 \, M_\odot$, and a Belt age of 40 Myr consistent with the stellar estimates. The observed star counts imply a supernova frequency of 20 to 27 supernovae per Myr in
the entire Belt. This rate falls to 17 to 20 supernovae per Myr using revised star counts. The uncertainty stems from that in the star counts and Belt age and, mostly, from the large uncertainty in the $\Gamma$ index between $-2.0$ and $-1.1$ at large mass. Using a size of $354 \times 232$ pc, the corresponding rate of 65 to 78 Myr$^{-1}$ kpc$^{-2}$ is 3 to 4 times the local Galactic one and is valid for the past few Myr. This rate stresses how actively the local medium has been heated and enriched by supernova remnants as well as irradiated by cosmic rays.

The rate is consistent with the existence of four 0.1–1 Myr old radio loops, the Local Bubble, and possibly the Vela supernova remnant near the rim. Vela Junior, alias RX J0852.0-4622 or G266.2-1.2, may be as close as 200 pc to be young enough to power the possible COMPTEL detection of $^{44}$Ti decay lines. The interstellar absorption of the X-ray emission, however, suggests a distance of 1–2 kpc, so a confirmation of the 68, 78, and 1157 keV lines by INTEGRAL is eagerly awaited. RCW 114, alias G343.0-6.0, may be a nearby evolved remnant, well into its radiative phase, that has expanded in a rather dense medium. Maps of the interstellar density do show a cavity 200 pc away in this direction, near the Belt rim.

Supernova shock waves are generally proposed as the sources of cosmic rays up to $10^{15}$ eV (see [15] for a review). The detection of synchrotron X-rays from various remnants (Cas A, SN 1006, G347.3-0.5, Tycho) lends further support to the diffusive acceleration of electrons up to tens of TeV. Direct observational evidence for the acceleration of ions is still searched for, but the indirect evidence becomes compelling. The Belt rate is globally consistent with the power of $2.3 \times 10^{44}$ J Myr$^{-1}$ kpc$^{-2}$ required to maintain the local cosmic-ray density for a standard supernova-to-cosmic-ray energy conversion efficiency of a few percent. However, the cosmic-ray spectrum should vary with source proximity in space and time. The fluctuations are particularly strong for the electrons above 50 GeV for which the synchrotron and inverse Compton radiative timescale is short, so they diffuse no further than several hundred parsecs from their accelerator. Adding the contributions from sources in the Galactic disc and in the Belt, with the respective rates quoted above, the average electron spectrum at Earth turns to be only slightly harder with the Belt than without, with a spectral index increase of 0.07 above 50 GeV. Yet, the currently measured spectrum may not be representative of the average, nor should it be uniform in the local interstellar medium. It should correlate with that in the nearby Ophiuchus and Taurus clouds, but not much with the spectrum in more remote places like Orion, Cepheus, Perseus, and Monoceros. The power per supernova required to sustain the local electron spectrum is reduced by 40 % when including the Belt, compared to a pure Galactic disc production. Cosmic-ray protons and primary nuclei do not suffer serious radiative losses, but the source clustering in the Belt also leads to an increased cosmic-ray density locally, to large fluctuations about the average, and to a slight softening of the average spectrum because the higher-energy particles diffuse away faster.

5 $\gamma$-ray sources and pulsars in the Belt

New facets of the Gould Belt activity have been brought to light at high energy with the discovery of a population of $\gamma$-ray sources associated with the unidentified $\gamma$-ray sources seen above 100 MeV by the EGRET telescope onboard the late Compton Gamma-Ray Observatory. A subset of 35 to 40 of these sources, among the steadiest, is gathering at medium latitude ($3^\circ < |b| < 30^\circ$) along the characteristic trace of the Gould Belt (see figure). The source distribution is significantly better correlated with the Belt than with other Galactic structures likely to display sources at medium latitude, such as a homogeneous spherical Galactic halo, or the local Galactic disc (with any scale height), or the 400 pc-thick disc of radio pulsars. This should come as no surprise since there is clear evidence, close to the Galactic plane, that unidentified $\gamma$-ray sources are linked to star-forming sites. What is puzzling, however, is that most of the sources lack conspicuous radio or X-ray counterparts.
Figure 4: Spatial distribution, in Galactic coordinates, of the 50 unidentified persistent EGRET sources $|b| > 3^\circ$.

The grey scale traces the column-density of local young stars ($< B_3$), convolved with the EGRET exposure.

despite their proximity. Whatever powers the $\gamma$-ray source emits most of its radiative energy in $\gamma$ rays. No clear picture has emerged yet as to the nature of these objects, but neutron star activity appears as a promising prospect. Other possibilities are unlikely. The sources are too bright in $\gamma$ rays to be unresolved gas clumps irradiated by the local cosmic-ray flux. The required mass of $\sim 10^4 M_\odot$ at 500 pc cannot have escaped the radio and IR surveys, even when considering radio beam dilution from unresolved clouds. Nor can they be slow, old neutron stars, wandering in the interstellar medium and accreting gas from a dense cloud for they would be $10^{2-3}$ times too rare and the maximum Bondi-Hoyle accretion power of $\sim 2 \times 10^{25}$ W that can be drawn from the surrounding HII region is 10 times too low. The accretion power reached for slowly spinning, highly magnetized neutron stars moving at 200–400 km s$^{-1}$ in the intercloud medium ($10^{-3}$ H cm$^{-3}$), though increased by Kelvin-Helmholtz instabilities in the shocked gas, is also orders of magnitude too low. Isolated accreting black holes are even more rare and compact objects accreting from a stellar companion, as well as microquasars, would shine too brightly in X rays. No source coincides with any of the numerous O Belt stars despite their highly supersonic winds with kinetic powers of $10^{28-29}$ W. Nearby supernova remnants would appear as extended $\gamma$-ray sources. Therefore, only pulsars are left as promising candidates even though the present models for pulsed emission predict too few of them.

13 radio pulsars from the ATNF catalogue are found with distances $< 1.5$ kpc and age $< 2$ Myr, but they are too few and too fast to show a correlation with the inclined Belt or with the Galactic plane. The narrow radio beams from many more may miss the Earth. Two young and energetic radio pulsars, Geminga and PSR B0656+14, are born inside the Belt, 0.35 and 0.11 Myr ago, respectively. The younger Vela pulsar exploded 11 kyr ago near the rim. Geminga and Vela are both conspicuous $\gamma$-ray pulsars and the detection of the third one above 100 MeV awaits confirmation. Geminga stands out as a unique example of a radio-quiet $\gamma$-ray pulsar. It is the intrinsically faintest $\gamma$-ray pulsar observed so far, but equally faint sources would have been easily detected anywhere inside or around the Belt if their radiation beam swept by us. How the luminosity evolves at older ages is model dependent. Population synthesis studies have been performed, both to provide information on the likelihood that these unidentified sources be radio-quiet $\gamma$-ray pulsars and to study the pulsar population born in the Belt.

Pulsars are produced in the simulations with a constant birth rate of 1–1.4 per century over the past billion years in the Galactic disc and of 20–24 per Myr in the expanding Gould Belt.
They evolve in the Galactic potential to the present time. Their initial period and magnetic field distributions are chosen to fit the $P - \dot{P}$ diagram of a thousand radio pulsars. Their radio and $\gamma$-ray beams evolve with their spin-down luminosity, $\dot{E}_{sd}$, as they get old. The slot-gap and outer-gap models\textsuperscript{2,7} for pulsed emission predict similar luminosity evolutions ($L_\gamma \propto \dot{E}_{sd}^{0.5}$ and $L_\gamma \propto \dot{E}_{sd}^{0.38}$, respectively). The beam apertures greatly differ in the two cases because of their different origins in the open magnetosphere. Radiation is produced in the slot gap in funnel-like beams deep inside the magnetosphere, above the polar caps, whereas the outer-gap fan-like beams originate near the light cylinder. It appears that the characteristic spatial signature of the Belt is preserved over several Myr despite its expansion, the rapid pulsar migration\textsuperscript{1}, and the blending with the Galactic pulsar population\textsuperscript{34,18}.

The results\textsuperscript{2,7} show that 4 slot-gap and 5 outer-gap radio-loud $\gamma$-ray pulsars of Belt origin should have been detected by EGRET, in reasonable agreement with the 2 or 3 detections. An extra 5 or 15 radio-quiet ones should appear as unidentified sources. The 3 times larger prediction of the outer gap model results from the much wider beam that can be seen at large angles. In both cases, Belt pulsars remain detectable for EGRET up to 2 Myr of age, i.e. much longer than for the more distant pulsars in the Galactic disc. With more detections with the future GLAST satellite, to be launched in 2007, the ratio of radio-loud to radio-quiet $\gamma$-ray pulsars will be an important clue to discriminate between pulsar models. Yet, both models fail to explain the number of sources associated with the Belt. The same conclusion is reached using a different scheme that yields an upper limit to the pulsar contribution at mid latitudes for a minimal choice of assumptions, namely that the beam geometry shrinks with age as the open magnetosphere and that the $\gamma$-ray luminosity scales with the spin-down power as for the known $\gamma$-ray pulsars\textsuperscript{18}. A total of 19 Belt $\gamma$-ray pulsars is obtained by fitting the spatial and flux distributions of all the unidentified EGRET sources near and away from the Galactic plane, without any radio population constraints. So, the origin of most of the unidentified Belt sources remains a puzzle.

Finding the Belt neutron stars would provide a unique opportunity to constrain pulsar models to older ages and a variety of aspect angles, and to study the progenitor mass threshold for producing a neutron star. As supernova relics, they would bring valuable insight to the cosmic-ray production efficiency, the abundance of explosive nucleosynthesis products, and to the filling factor of hot interstellar gas and its connection to the halo. In other words, the Gould Belt is a lively and fascinating, but complex and out of the ordinary place to live in and explore.

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