The spiral structure of the Galaxy revealed by CS sources and evidence for the 4:1 resonance

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ABSTRACT

We present a map of the spiral structure of the Galaxy, as traced by molecular carbon monosulphide (CS) emission associated with IRAS sources which are believed to be compact H II regions. The CS line velocities are used to determine the kinematic distances of the sources in order to investigate their distribution in the galactic plane. This allows us to use 870 objects to trace the arms, a number larger than that of previous studies based on classical H II regions. The distance ambiguity of the kinematic distances, when it exists, is solved by different procedures, including the latitude distribution and an analysis of the longitude–velocity diagram. The study of the spiral structure is complemented with other tracers: open clusters, Cepheids, methanol masers and H II regions. The well-defined spiral arms are seen to be confined inside the corotation radius, as is often the case in spiral galaxies. We identify a square-shaped sub-structure in the CS map with that predicted by stellar orbits at the 4:1 resonance (four epicycle oscillations in one turn around the galactic centre). The sub-structure is found at the expected radius, based on the known pattern rotation speed and epicycle frequency curve. An inner arm presents an end with strong inwards curvature and intense star formation that we tentatively associate with the region where this arm surrounds the extremity of the bar, as seen in many barred galaxies. Finally, a new arm with concave curvature is found in the Sagitta to Cepheus region of the sky. The observed arms are interpreted in terms of perturbations similar to grooves in the gravitational potential of the disc, produced by crowding of stellar orbits.

Key words: Galaxy: disc – Galaxy: fundamental parameters – Galaxy: kinematics and dynamics – Galaxy: structure.

1 INTRODUCTION

While the spiral structure of external galaxies is clearly traced by CO or by H II regions, obtaining the equivalent of a ‘face-on’ map of the spiral arms of our Galaxy is a more tricky task. Since the Sun is situated close to the middle plane of the disc, the arms are seen superimposed. In addition, due to the high visual extinction in the disc, it is difficult to obtain reliable distances to stars from their absolute and apparent magnitudes. To determine the distances of H II regions or molecular clouds in the galactic plane, the most used tool has been the kinematic method. In this method, the velocity of the object, obtained from observations of radio recombination lines or of molecular lines, is compared to the predicted velocity as a function of distance, based on the rotation curve. The main problem that one has to face is the distance ambiguity that affects the sources situated within the solar circle, which represents a large portion of the galactic disc. In this Galactic zone the method gives two solutions, and some additional information is required to decide which is the correct one. Another source of uncertainty is the distance scale itself, which depends on the particular choice of the kinematic model of the Galaxy.

One of the first maps of the spiral arms based on star formation regions covering a large part of the Galactic plane was published by Georgelin & Georgelin (1976); in that work, the known H II regions were fitted by four main spiral arms. Since then, new radio recombination line surveys have been completed (e.g. Caswell & Haynes 1987; Downes et al. 1980; Lockman 1989; Wink, Wilson & Bieging 1983) and many papers have been devoted to resolving the distance ambiguity by searching for absorption lines at a velocity higher than that of the source. The presence of such lines is a strong argument in favour of the more distant solution (Kuchar & Bania

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large rotation velocity $V_0$ of the LSR. If a large velocity scale is used (numbers are given below), a given difference of velocity between the LSR and the source is reached in a shorter distance. Furthermore, taking into account the minimum in the rotation curve that exists close to the Sun also contributes to better results, since again larger velocity differences can be reached on shorter distances. We next argue that these hypotheses on the rotation curve are reasonable in light of recent studies.

In the last decade or even earlier, many authors have adopted $R_0 = 7.5$ kpc (Racine & Harris 1989; Reid 1993, among others). This shorter Galactic scale, compared to the IAU-recommended 8.5 kpc value, is supported by VLBI observations of H$_2$O masers associated with the Galactic centre. More recently, infrared photometric studies of bulge red clump stars resulted in $R_0 = 7.52 \pm 0.10$ kpc (Nishiyama et al. 2006), while astrometric and spectroscopic observations of the star S2 orbiting the massive black hole in the Galactic centre taken at the European Southern Observatory VLT (Eisenhauer et al. 2005) gives $7.94 \pm 0.42$ kpc. Bica et al. (2006), revisiting the distribution of globular clusters, determined $R_0 = 7.3 \pm 0.2$ kpc.

The shorter scale has often been taken jointly with a smaller $V_0$, about 190 km s$^{-1}$, since the ratio $V_0/R_0$ as derived from Oort’s constants ($V_0/R_0 = A - B$) had a widely accepted value of 25 km s$^{-1}$ kpc$^{-1}$. Note that $V_0/R_0$ is the same as the angular rotation velocity of the LSR, hereafter denoted as $\Omega$. An interesting independent measurement of $\Omega$, which does not depend on the Galactic rotation curve, is that of Backer & Sramek (1999), who measured the proper motion of Sgr A at the Galactic centre, obtaining $6.18 \pm 0.19$ mas yr$^{-1}$, which is equivalent to $29.2 \pm 0.9$ km s$^{-1}$ kpc$^{-1}$ (in what follows, the units are always km s$^{-1}$ kpc$^{-1}$). The origin of the discrepancies in the determination of $\Omega$ seems to be the fact that the method of Oort’s constants is only valid if the rotation curve is quite smooth, which is not the case in the solar vicinity. Olling & Merrifield (1998) verified that the Oort’s constants A and B differ significantly from the general $V_0/R_0$ dependence, in the solar neighbourhood. Olling & Dehnen (2003) argued that the most reliable tracers of the ‘true’ Oort’s constants are the red giants, and derived $A - B = 33$. Among recent results, Branham (2002) obtains $\Omega = 30.3$, Fernández, Figueras & Torra (2001) $\Omega = 30$ and Miyamoto & Zhu (1998) $\Omega = 31.5$, from the kinematics of OB stars; Metzger et al. (1998) obtained 31 from Cepheid kinematics and Mendez et al. (1999) 31.7 from the Southern Proper Motion programme. This discussion tells us that it is quite reasonable to adopt $R_0 = 7.5$ kpc and $V_0$ about 220 km s$^{-1}$.

In a study of the epicycle frequency in the galactic disc, based on the spatial velocities of open clusters, Lépine, Dias & Mishurov (2008, hereafter LDM) argued that it was necessary to take into account a narrow minimum in the rotation curve at about 8.5 kpc (using $R_0 = 7.5$ kpc) to fit the epicycle frequencies (see that paper for other references on the minimum; we now prefer 8.8 kpc).

The rotation curve that we adopted is quite flat (except for a local minimum at about 8.8 kpc), and is close to that derived by Fich, Blitz & Stark (1989). The curve is conveniently fitted by exponentials and a Gaussian (units are km s$^{-1}$ and kpc):

$$V = 360 e^{-r/(3.1-0.09)r} + 270 e^{-r/80-(3.4/r)^2} - 15 e^{-(r-8.8)/0.8}.$$  (1)

The first two components contain terms in $(1/r)$ and $(1/r^2)$ inside the exponential function, which produces a decrease of their contribution towards small radii. The last term represents a Gaussian minimum. Since we do not use the curve for radii smaller than

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shows, however, that there is no systematic difference between the
two methods, which could produce distorted or incorrect size of the
spiral structure.

We completed the CS sources with a short list (18) of methanol
maser sources for which precise measurements of parallax are avail-
able (Rygl et al. 2010; Sanna et al. 2009, and references therein).
The methanol masers are associated with star-forming regions and
are therefore tracers of the spiral structure. The location of the
masers is shown in Figs 7–10 in which we present maps of the CS
sources on the galactic plane, and is useful to confirm the position
of the arms. Other tracers are commented later.

2.1 Velocity perturbations with respect to the rotation curve

The use of a well-behaved or classical rotation curve like that of
equation (1) brings some difficulties. For a relatively large number
of sources, there are no kinematic solutions for the distances. For
instance, between galactic longitudes 28° and 33° the BNM cata-
logue contains several tens of sources with LSR velocities of the
order of 120 km s⁻¹. These velocities are larger than the maximum
velocity along the line of sight (or velocity at the subcentral point)
derived from equation (1), for this range of longitudes. A rotation
curve with a much larger velocity at about 6 kpc from the centre
would be required to obtain solutions in the usual way. Such a ro-
tation curve is unlikely on the basis of other observations including
those at longitudes symmetrical with respect to the Galactic centre.
The best explanation is that we are seeing non-circular velocities.
The way that we deal with this problem is the following: each time
the computer program does not find a normal solution, it adds (or
subtracts) a constant velocity (say 20 km s⁻¹) to the theoretical curve
of velocity versus distance and looks again for a solution. In most
anomalous cases a solution can then be found. Of course, a source
with anomalous velocity like in our example given above cannot be
far from the subcentral point, and we could just attribute a distance
equal to that of the subcentral point. The solution that we adopted is
preferable because it avoids crowding of sources at the subcentral
point, and smoothly distributes sources with different velocities at
different distances. It might seem that it would have been preferable
or more self-consistent if, to compute distances, we had taken into
account the non-circular velocities expected from the stellar orbits
and resonances of the model discussed in this work. In practice, this
would be very difficult to do, since, as it will be seen in later sections
and as can be inferred from Fig. 5, the velocity perturbations are
not a function of position only. Orbits of different nature can cross
each other and produce different velocity perturbations at a same
position in the plane.

3 RESOLVING THE DISTANCE AMBIGUITY

Starting from the BNM catalogue, and removing from it the sources
with no CS detection, or with no IRAS identification, we get 852
sources. We also remove 99 sources situated within ±10° from the
galactic centre and from the anti-centre, where kinematic distances
are not valid; the remaining list contains 753 sources. Of these, for
236 sources there is only one kinematic solution, because they are
outside the solar circle (circle with radius R⊙ centred on the Galactic
centre). For 500 sources two kinematic solutions were found and
for 16 sources no solution was found, even with the non-circular
velocity correction discussed in the last section.

We next describe several criteria that we used to decide which
of the two solutions is the correct one. Conflicts between different
criteria were very rare. If more than one criterion points towards the
same (near or far) solution, then this solution has a high probability to be correct.

A first very simple test is the galactic latitude. The CS sources are very concentrated in the galactic plane, usually situated within 50 pc of the plane. This means that a source with $|b| \geq 0.6$ has a large probability of being a nearby one. However, there are exceptions. In regions closer than 5 kpc to the galactic centre, the near and far solutions are both far from the Sun and not very distant one from the other; in these cases, this criterion loses its efficiency. Besides this, in some regions distant from the galactic centre, the warp of the Galaxy affects the average latitudes. For instance, for longitudes $330^\circ -350^\circ$, many sources have galactic latitudes around $-0.9$; in these cases a distant (correct) solution is found at a distance around 13 kpc from the Sun.

A second test makes use of the radioastronomical data on antenna temperatures $T$ and linewidths $\Delta V$ given in the CS sources catalogue. It is reasonable to suppose that there should be a correlation between the infrared and radio flux densities, but that possibly the angular size of the two components sources are different and their ratio could depend on distance. We present in Fig. 2 the integrated IRAS flux, defined in a simple way as the sum of $\lambda f(\lambda)$ for the 12 $\mu$m, 25 $\mu$m and 60 $\mu$m (the 100 $\mu$m band is excluded as it is too contaminated by background radiation) versus $T \times \Delta V$ of CS lines. In the figure, we plotted the 236 sources with known distances (sources with only one kinematic solution). The IRAS integrated flux is normalized to a distance of 1 kpc (in other words, it is the equivalent of an absolute flux).

Of course, we would expect to find intrinsically brighter sources among the more distant ones, since weak sources at large distances would not be detected. A surprise is that the distant sources are much brighter. This has to be explained by the brightness distribution and space density of the sources. As a comparison, let us remind the reader that the list of the 25 stars nearest to the Sun and the list of the 25 brightest stars in the sky have only three stars in common (α Centaurus, Sirius and Procyon). In Fig. 2 we plotted with different symbols sources that are closer and farther than 5 kpc, and an empirical separating line was drawn. Below the line the sources have 95 per cent probability of being closer than 5 kpc. This is a distance which, for the sample with two solutions for the distance, is most often situated between the nearby and the distant solution. In practice, this criterion can be used in the following way: we compute the distance-corrected flux for both the near and the far solution; if both are below the line shown in Fig. 2, then the near solution is very probably the correct one.

Another criterion to choose the correct solution for CS sources is to look for the coincidences with H II regions for which the distance ambiguity has already been solved. It is not rare that the CS sources have coordinates and velocities close to those of an H II regions, so that they probably belong to the same molecular cloud. For a number of H II regions (see references in the Introduction) some criterion like the presence or absence of an H I absorption line at a high velocity was able to point to the correct solution.

Finally, we also made use of the longitude–velocity diagram. This diagram is convenient, since all the sources can be placed on it without problems of ambiguity. Let us first remark that spiral arms in the first and fourth quadrants of the galactic plane, and situated at distances smaller than $R_0$ from the Sun, present ‘tangential points’, that is, a line-of-sight tangential to them can be drawn. These spiral arms have corresponding loci in the $l - v$ diagram in the form of loops that reach a maximum value of longitude and then go back to smaller values. For this reason all the sources that are close to the lines of maximum velocities in the $l - v$ diagram, that is, close to a line going from $l = 90, v = 0$ to about $l = 20, v = 140$, for positive longitudes, and to a line from $l = -20, v = -140$ to $l = -90, v = 0$ (see Fig. 3), are sources near a tangential direction to a spiral arm. For sources situated near the tangential directions, the near and far solutions are close together, so that the problem of the distance ambiguity is not important. On the contrary, for sources that are about halfway between these limiting lines and the centre of the diagram ($l = 0, V = 0$), the two solutions are distant.

4 RESULTS AND DISCUSSION

Fig. 4 shows the final result concerning the mapping of the spiral structure with CS sources, without any attempt to fit the arms. In this figure, we used three different sizes for the symbols representing the CS sources; the sizes are proportional to the logarithm of the absolute flux (antenna temperature $\times$ linewidth $\times$ square of the distance). Basically, our results confirm the main aspects of the spiral structure revealed by the studies of H II regions by Russeil (2003) and PDD. For instance, if we move horizontally across the figure, to the right or to the left of the Galactic centre, we find roughly three spiral arms on each side, like the previous works. There are departures from the pure logarithmic spirals, with segments of arms
work on the morphology of spiral arms that, in general, the arms are well defined (they look like star formation ridges) and are symmetrical inside corotation, and are broader and more diffuse outside corotation. This corresponds well to what happens in our Galaxy, in which the well-defined arms are almost all contained inside the corotation circle. Several ‘star formation ridges’ seem to terminate at corotation. This is better seen in Fig. 8, which presents a zoom of the solar neighbourhood, where two arms terminate at corotation.

4.2 The fitted structure and the 4:1 resonance

Before presenting the fits to the spiral structure, we must clarify what we understand by spiral arms. The model that we adopt is based on the ideas of Kalnajs (1973). Stellar orbits of successive increasing radii in the disc are organized in such a way that they get close together in some regions, which consequently present an excess of stellar density. The overdense zones form elongated gravitational potential wells in the disc, which are the spiral arms. The gas of the disc falls into the potential wells, reaching high densities that favours star formation. Consequently, the map of the star formation ridges coincides with the map of the regions where the stellar orbits approach each other. The initial organization of the stellar orbits is not a question to be debated here; it is probably due to the tidal effect of an external galaxy which passed close to the Milky Way. A consequence of this interpretation of the physics of spiral arms is that the location of the arms is mainly determined by the stellar dynamics, and not by the hydrodynamics of the gas. The perturbed stellar orbits are not closed ones in the inertial frame of reference of the Galaxy, but it is possible to find a rotating frame of reference in which the orbits are closed, so that stable spiral arms can be observed. The rotation velocity of that frame is the pattern speed. A stellar orbit is closed if the epicycle frequency (the frequency at which a star oscillates around the unperturbed circular orbit) is a multiple of the angular frequency of the orbit around the galactic centre in the pattern frame.

Amaral & Lépine (1997, hereafter AL) performed a study of the stellar orbits and spiral structure for a potential similar to that of our Galaxy. We present in Fig. 5 an updated version of that work; the method used to trace the orbits is exactly the same as that of

![Figure 5. A model of the spiral structure of the Galaxy based on the crowding of stellar orbits to explain the arms.](image-url)
The distribution of CS sources in the galactic plane, with fitted rotation curves and the location of the main resonances, for a pattern rotation velocity of 24 km s$^{-1}$ kpc$^{-1}$. The $\Omega \pm \kappa / 2$ curves are shown as continuous lines, and the $\Omega \pm \kappa / 4$ curves as dot–dashed lines. Corotation is at 8.4 kpc. ILR and OLR at 2.5 and 14 kpc, respectively, and the 4:1 resonance at 6.2 kpc. Distances on the axes are in kpc.

Since in our Galaxy the corotation radius and the Inner Lindblad Resonance (ILR, which we discuss later) are known, it is easy to infer where the 4:1 resonance is expected (see Fig. 6): at about 6.2 kpc from the centre. This is the radius of the guiding centre; if we consider a typical radial amplitude of the epicycle oscillation of about 10 per cent of the radius of the orbit, the maximum distance from the galactic centre (the corner of the square) could reach about 7 kpc. Indeed, we claim that there is convincing evidence that this resonance is observed, as shown in Fig. 7. In that figure, we fitted square-shaped arms obtained by combining a circular orbit with radius 6.2 kpc plus an epicycle perturbation with radial amplitude equal to 0.65 kpc (the radial ‘amplitude’ of the elliptic epicycle is the semiminor axis $b$, with $a/b = 1.5$; see LDM). The phase of the epicycle (or orientation of the square orbits) was adjusted to fit the data. It can be seen that many CS sources fit the two sides of the rounded corner of the square-shaped arm situated close to the Sun (in blue), as well as an entire side of the same square. The other square-shaped orbit (in red), rotated 45° with respect to the first one, also presents many CS sources along its sides. Note that part of the corner close to the Sun, as well as the corner on the opposite side of the Galaxy, is not observed because the sources with longitudes 10° on each side of the Galactic centre are not plotted (the kinematic method does not permit to calculate the distances in those directions). Furthermore, the absence of sources in distant regions opposite to the Galactic centre, particularly at longitudes between 330° and 350°, is possibly due to observational limitations like the limit of sensitivity of the IRAS survey based on which the CS sources were searched, and/or the warp of the Galaxy which favours negative longitudes (the survey was limited to $\pm 2°$ in these directions).

In order to overcome the problem of the absence of CS sources in a range of longitudes due to the kinematic distances, we also plotted the positions of the open clusters in the galactic plane in Figs 7 and 8, and of the Cepheids, open clusters and H$\alpha$ regions in Figs 9 and 10. The sample of Cepheids and the method of calculation of their photometric distances were described in a previous section. The open clusters were selected with an upper age limit of 15 Myr (the catalogue of Dias et al. 2002, frequently updated, is available at www.astro.iag.usp.br/~wilton). The interstellar extinction limits the observation of Cepheids and of open clusters to a small portion of the galactic plane, but these objects are useful tracers in the solar neighbourhood. The H$\alpha$ regions were added since they are the most traditional tracers, and combined with the CS sources, they provide a large number of sources distributed all over the Galactic plane. We used the catalogue of H$\alpha$ regions of Russell (2003), but we recalculated the distances with the same kinematic distance program described in Section 2; in the cases of distance ambiguity we adopted the same option (near or far) of Russell.

The Cepheids and clusters clearly delineate a part of the corner of the square-shaped orbit at the 4:1 resonance which was lacking. The same rounded 90° break of that spiral arm was also observed by...
Figure 8. The solar neighbourhood seen in an expanded scale. The colours of the fitted arms, the colours of the symbols and the label of the arms (1–6) are the same as in Fig. 7. Arm 7, in red, is a straight arm that fits many sources; it appears more clearly in Fig. 9, with additional tracers. Arms 8 and 9, in dark blue and in red, are short logarithmic arms. Arm 9 is the one which passes nearest to the Sun; it contains the nearby star-forming regions in Sco, Lup, Cen and Crux. It is represented as crossing the Sagittarius–Carina arm, but this crossing is uncertain. Arm 10, represented as a green straight line, is the Orion arm or Orion ‘spur’; it is possibly a bifurcation of the Sagittarius–Carina arm. Its position is well determined, since it contains three maser sources with parallax measurements. Arm 11, represented by a light blue straight line, is the Perseus arm; except in the region nearest to the corotation circle, where several methanol masers are present, its position and shape are uncertain. The dotted line represents the corotation radius. The Sun is at position (0,0).

Majaess et al. (2009) using Cepheids. Note that the amplitude of the radial perturbation is a parameter that strongly affects the shape of the corner, which can range from rounded to a sharp peak, without affecting too much the rest of the square. One may wonder why Cepheids, which are stars with ages up to $10^8$ yr, and CS sources associated with compact H II regions, with ages less than 10 million years, could be sharing almost the same arm. Is it not expected that the stars leave the spiral arms as soon as they form? This is true for ‘normal’ logarithmic spiral arms, since logarithmic spirals are not acceptable stellar orbits. In the case of the 4:1 resonance the square-shaped potential well, better described as a potential channel or groove, is formed with the contribution of many stellar orbits which are not square-shaped, as can be seen in Fig. 5. However, once the gravitational potential channel exists, the gas will flow along it, and the stars that form from that gas have initial velocities directed along the direction of the groove, which means along the square-shaped orbit. Since this coincides with an expected stellar orbit in the galactic potential at that radius, the stars that are injected with the correct velocity (magnitude and direction) will stay on that orbit. We recognize that the ideas concerning the nature of spiral arms expressed here depart from the traditional ones on density waves. As it was commented by Dobbs et al. (2010), there is much ambiguity in the literature as to what is meant or understood by the phrases ‘density waves’ or ‘density wave theory’. The classical interpretation of spiral arms as shock waves has been up to now unable to predict the preferential directions of the initial velocity of stars formed in the arms, neither it is able to explain anomalous shapes of spiral arms like the ‘square-shaped’ ones. Our research group has performed hydrodynamic simulations of the interaction of interstellar gas with spiral arms, first relatively simplified ones (Lépine, Mishurov & Dedikov 2001), and, recently, more sophisticated ones (yet unpublished). We have learned that when the gas penetrates an elongated gravitational potential well (or potential groove) produced by a crowding of stellar orbits, it strongly accumulates in the groove and flows along the groove. The magnetic field does not inhibit this process, since the field lines are usually aligned in the direction of the arms. However, it is not essential to share our understanding of the nature of spiral arms to benefit from the present paper, nor do we claim that all the spiral arms have the same physical nature.

Coming back to the observations, Fig. 10 reveals the impressive complexity of the spiral structure in the solar neighbourhood. There is a risk that some of the lines that we traced are not strictly correct and connect structures that are not related one to the other. A detailed study taking into account space velocities, age, metallicities or average positions in the Z direction (perpendicular to the galactic plane) of the tracers might reveal the existence of ‘families’ of objects and confirm the connections that we have drawn. The figure also shows that there are ‘arms’ that cross each other, which is not surprising in the interpretation of arms in terms of stellar orbits like those in Fig. 5, but would be more difficult to explain in a classical density wave interpretation.

4.3 The connection with the external structure

Since we commented that several arms traced by the CS sources seem to terminate at corotation, this may raise the question of...
whether the spiral structure outside corotation is connected to that of the inner region. There is clear evidence in other galaxies that the main arms are able to cross corotation. For instance, in M51 the corotation radius is 5 kpc or 120 arcsec (Sheepmaker et al. 2009); at this radius one can see a gap in the H\textsc{i} density in one of the two main arms (see the H\textsc{i} map of Walter et al. 2008), but the same arm seen in visible light shows no discontinuity.

In our Galaxy too, we can see connections between the internal and external spiral structures. For instance, the Carina arm, which in our Fig. 4 reaches the corotation circle at about galactic longitude $\ell = 300^\circ$, can be seen in fig. 2 of Levine, Blitz & Heiles (2006, hereafter LBR) to have a natural continuation in an H\textsc{i} arm which can be followed up to $\ell = 320^\circ$ (note that the circle represented by LBR in their figure is the solar circle, not corotation). An arm mapped by Vázquez et al. (2008) in the third quadrant of the Galaxy seems to be a continuation of the arm that passes less than 1 kpc from the Sun in the direction of the anti-centre (fitted by a green straight line in Fig. 10).

A relatively large ensemble of young objects containing methanol masers, Cepheids and open clusters, but only a few CS sources, are present in the direction of Perseus, $l = 130^\circ$, just outside corotation. It seems to be connected with the structures in the inner side of corotation. For the moment it is difficult to say if this structure is part of the outer arm that we show in blue, or if it is a ‘loop’ in stellar orbits (we comment on these structures in the next section).

In our Galaxy, only for some of the arms there seems to be insufficient gas density to form stars near the ‘Cassini’ gap in the gas distribution observed at corotation; this does not necessarily mean that the grooves in the gravitational potential produced by stellar orbits are absent. Note that the numerical investigations of stellar orbits usually skip the radii close to corotation because the integration time to obtain an orbit around the Galactic centre becomes very long.

### 4.4 The Sagitta–Cygnus outer arm with concave curvature

An interesting feature appears in Figs 7 and 9, which is an arm at about 10 kpc from the Galactic centre, in the range of longitudes about 80° to 140°. This arm is traced not only by CS sources but also by the Cepheids, which is a confirmation of the correctness of the distance scale. This feature was not recognized as an arm by either PDD nor Russell (2003) but it is clearly seen in the H\textsc{i} maps of LBR (taking into account the difference in scale). Part of it appears in the map of molecular clouds by Efremov (1998), and is represented by Vallée (2008) as a very long logarithmic spiral extending from Norma to Cygnus.

The particularity of this arm, also seen in the map of LBR, is that it presents a reverse curvature. Instead of attributing its shape to an interaction with an external galaxy, we prefer to explain it as a normal arm shape associated with a resonance. Like inside corotation, as previously discussed, we expect to have again outside corotation, but still within the OLR, a collection of closed orbits with a number of ‘corners’. If the radial amplitude of the epicycle perturbation is a large fraction of the radius of the unperturbed orbit, the corners appear as narrow peaks pointing outwards or even small loops in which the stars reverse their direction of motion, in the frame of reference of the pattern. In these cases, in the regions between two corners the curvature of the orbit is concave. In regions relatively distant to the centre, the axisymmetric potential of the Galaxy becomes shallow, and small energy perturbations produce larger radial amplitudes. The curve that we plotted on the external arm is only an illustration of the type of curve that can be obtained, and not a final fit to the data. We also plotted a straight segment to roughly fit the sources in the upper part of the figure, just outside corotation. In the next section we comment on the existence of such structures in other galaxies.

### 4.5 Additional comments on polygonal arms

If one looks carefully, in many cases, what seems at the first glance to be a logarithmic spiral arm is better approached by a sequence of straight segments with an angle between them (examples are M101, NGC 1232 and M51). Chernin et al. (2001) present a list of a large number of galaxies with such ‘polygonal’ structures, which include some of the nearest and best known spirals. Chernin (1999) explains the straight portions as local flattening of the shock fronts that happens because a flat shock is a more stable configuration than a curved one. Our interpretation is different, since we consider that the shape of the arms is determined by stellar orbits, and not by the gas. Our model predicts that for large perturbation amplitude, a loop appears in the connection between two straight segments, like the one that we draw in Fig. 9. Such loops are observed (see e.g. the CO map of M51 by Hitschfeld et al. 2009, in the lower left of their fig. 5, and the image of M101 available at the site apod.nasa.gov/apod/ap030310.html, with two straight segments which seem to cross each other and make the connection through a big loop, at the top of the figure). We do not exclude the existence of such loops in the 4:1 orbits of our Galaxy (the Gould Belt?), but this is left for future work.

In M101 and NGC 1232, one can see many parallel segments of arms; this is a justification for using two almost parallel segments, in the upper part of Fig. 9, instead of attempting to fit a logarithmic spiral.

Concerning square structures in particular, Patsis, Grosbøl & Hiotelis (1997) concluded from a study of the morphology of spiral arms and interarm regions in SPH models that the 4/1 resonance...
generates a clear signature in galaxies, namely a bifurcation of the arms typical for the morphology of normal, late-type, grand design spirals. Square structures are observed, for instance, in the inner parts of M51 (see the CO map of the inner region by Aalto et al. 1999) and of NGC 5247 (Grosbol & Dottori 2008, see their fig. 4).

4.6 The connection to the bar

In the same work on the morphology of spiral arms that we already mentioned, EE95 state that the bars of spiral galaxies can be separated into two types, the large bars and the small bars. The small bars terminate near the ILR of the spiral structure. This is clearly the case for our Galaxy. The spiral arms can be followed down to about 3 kpc from the centre, as can be seen in Fig. 7, which is close to the ILR of the spiral structure, as derived from the rotation curve and pattern speed (see Fig. 6).

Many authors refer to the ‘molecular ring’ of our Galaxy to describe the fact that there is a larger density of molecular clouds in the range 3 to 5 kpc from the centre. This expression may give the impression that there is, indeed, a ring, which would be a closed arm-like structure. It is possible to fit a closed ellipse to the CS sources near the ILR, but this is not the best fit; segments of spiral arms seem to be a better approach. We tentatively present the position of the bar with 3 kpc each side of the centre in Fig. 9; the angle of the bar with respect to the line joining the galactic centre to the Sun is 24°, as determined by Nikolaev & Weinberg (1997) using IRAS data. At the bar extremity nearest to the Sun, one can see a spiral arm ending in a curvature that surrounds the bar, like in many barred galaxies (see pictures of NGC 1300, NGC 1073, etc.). The precise position of this part of the arm is confirmed by the presence of two maser sources with direct measurement of distance by parallax. This suggests that in our Galaxy the extremities of the bar are attached to the spiral structure, similarly to what happens in most barred spirals, and that, possibly, the rotation velocity of the bar is the same of the spiral pattern (about 25 km s⁻¹ kpc⁻¹). For the moment the rotation velocity of the bar is uncertain, since precise measurements of velocities of stars really associated with the bar are difficult due to the heavy interstellar extinction, and the velocity anomalies of stars situated near to the Sun are only affected by the local spiral structure. We recognize that this question is still a matter of debate (e.g. Gerhard 2010).

5 CONCLUSIONS

The CS sources of the catalogue of BNM are very good tracers of the spiral arm structure of the Galaxy, covering a large part of the disc and providing a clearer picture than that obtained with the Hβ regions. A number of details that were not previously recognized could be observed in the present study. The arms inside the corotation circle are thin and well defined, looking like star formation ridges, while outside corotation they become broader and not so well defined. This is a general property of spiral galaxies which was observed by EE95.

We were able to recognize the square-shaped stellar orbits of the 4:1 resonance, very similar to those that are predicted from an analysis of the distribution of closed stellar orbits, using a model based on the potential of our Galaxy. One of the corners of these orbits is found to be at about 1 kpc from the Sun. This discovery is rich in consequences that have not yet been explored. The model shows that there are orbits of different sub-structures overlapping in the solar neighbourhood. The stars from different orbits are expected to have different space velocities and possibly different metallicities, as they were born at different galactic radii.

The 4:1 resonance is a fundamental structure of the disc, and its identification, added to the recent discovery of the ring-shaped gap in the gas distribution at corotation, provides a robust self-consistent understanding of the spiral structure. The measurements of fundamental quantities like the pattern rotation velocity and the epicycle frequency curve, recently performed by our group, are in good agreement with the location of the main resonances that we advocate.

In the inner regions of the galaxy, we observed a structure which seems to be the inner end of a spiral arm that makes a turn at the extremity of the bar, as seen in many galaxies. Since in addition to the CS sources there are two masers with distances directly determined by parallax in this arm extremity, the precise distance can possibly restrict the models of the bar.

Another interesting result is the observation of an arm with concave curvature at about 10 kpc from the Sun (in our short scale) in the longitude range 80° to 140°. We call it the Sagitta–Cepheus outer arm, since it is not coincident with the arm called Cygnus arm in the literature, usually said to be beyond the Perseus arm. This new arm is inside the OLR and its shape is not an unexpected one from the models of stellar orbits, which produces concave orbits for large enough epicycle perturbation amplitude.

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