The corotation gap in the Galactic H\textsc{i} distribution

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Accepted 2009 August 20. Received 2009 August 18; in original form 2009 March 10

ABSTRACT

We used the H\textsc{i} data from the LAB Survey to map the ring-shaped gap in H\textsc{i} density that lies slightly outside the solar circle. Adopting \(R_0 = 7.5\) kpc, we find an average gap radius of 8.3 kpc and an average gap width of 0.8 kpc. The characteristics of the H\textsc{i} gap correspond closely to the expected ones, as predicted by theory and by numerical simulations of the gas flow near the corotation resonance.

Key words: Galaxy: disc – Galaxy: general – Galaxy: kinematics and dynamics – Galaxy: structure – galaxies: spiral.

1 INTRODUCTION

Since the first H\textsc{i} observations, the existence of a ring-like minimum in the gas density distribution in the Galaxy has been apparent; see for example, Kerr (1969) and Burton (1976). In these works, the authors found a gas density deficiency at a radius of approximately \(R = 11\) kpc, assuming \(R_0 = 10\) kpc, but did not map it in detail nor propose an explanation for it. This radius would be about \(R = 8.3\) kpc, if we assumed \(R_0 = 7.5\) kpc. It is tempting to associate this gap with the corotation radius (\(R_c\)), namely the radius at which the rotation velocity of the spiral pattern coincides with the rotation curve of the gas and stars. This association is suggested by the fact that it has been shown, based on various arguments and methods, that corotation is close to the orbit of the Sun (Marochkin, Mishurov & Suchkov 1972; Crézé & Mennessier 1973; Amaral & Lépine 1997, hereafter AL; Mishurov & Zenina 1999a,b; Lépine, Mishurov & Dedikov 2001, among others). More recently, Dias & Lépine (2005, hereafter DL), using a sample of open clusters, determined \(R_c\) by measuring the spiral pattern speed \(\Omega_p\). The authors performed tests with various rotation curves and \(R_0\) values, obtaining \(R_c = 8.1 \pm 0.6\) kpc for \(R_0 = 7.5\) kpc, and argued that this determination is almost independent on the rotation curve used.

The papers mentioned above do not all adopt the same Galactic parameters, but they are in agreement, with values of \(\Omega_p\) proportional to \(V_0\) so that \(R_c\) is always close to \(R_0\). However, there are also in the literature many determinations of \(\Omega_p\) giving quite different values, and even some papers proposing the existence of multiple pattern speeds. Although the value of \(\Omega_p\) is not the focus of the present paper, we will next comment on a few of those results. Naoz & Shaviv (2007, hereafter NS), based on a similar analysis of the same data as used by DL, argued that the spiral arms situated in the solar vicinity have different velocities, and reached the surprising conclusion that the Carina arm (which is usually considered to be a normal arm, well fitted by a logarithmic spiral) is made of two superimposed components with different rotation speeds. What is the origin of the contradiction between the results of DL and NS? In their analysis, DL used two methods to retrieve the birthplaces of the clusters. One is a simplified analysis that assumes that the clusters move in pure circular orbits with constant velocity \(\Omega(r)\); the second method performs numerical integration of the orbits, taking into account the observed space velocities (radial velocities and proper motions) of the clusters. NS performed only the simplified analysis, with no integration of the orbits, and this could explain the discrepancy. In a more recent paper, Lépine, Dias & Mishurov (2008) showed that the clusters have typical birth-time velocities of the order of 10 km s\(^{-1}\) with respect to their local standard of rest (the velocity of the rotation curve at the birthplace). This means that the epicycle motion cannot be ignored for young objects and that the constant-velocity approximation is not satisfactory for precise measurements. The anomaly of the velocities of the young stars in the Carina arm is known (Humphreys & Kerr 1974). Other measurements tend to favour DL’s results. Fernández, Figueras & Torra (2001) analysed the spiral structure of the Galaxy using samples of OB stars and of Cepheids and estimated \(\Omega_p\) to be about 30 km s\(^{-1}\)kpc\(^{-1}\), reaching the conclusion that corotation is near the solar orbit. Examining the details of their analysis, it can be seen that the OB stars have large errors in distances (see fig. 1 of Torra, Fernández & Figueras 2000, in which the sample is described), whereas the sample of Cepheids is much better in this respect. Fernández et al. note that the Cepheids of their sample are mostly situated in the Carina-Sagittarius arm. These stars have typical ages of about 10\(^7\) yr, being older than the OB stars, which minimizes the problem of initial velocity. The values of \(\Omega_p\) that they obtain with their model ‘D’ (the model that corresponds to the smaller value of \(R_0\)) agree, within the small errors quoted by the authors, with \(\Omega_p\) obtained by DL (24 km s\(^{-1}\) kpc\(^{-1}\)). Avedisova (1989) also paid special attention to the Carina-Sagittarius arm, using a precise method, and...
concluded that $\Omega_0$ is $26.8 \pm 2.2$ km s$^{-1}$ kpc$^{-1}$, in agreement with DL and Fernández et al. In contrast with the methods based on direct observations of samples of stars or clusters, gas dynamics (e.g. Bissantz, Englmaier & Ottvin 2003; Rodríguez-Fernandez & Combes 2008) and N-body or test-particle simulations (e.g. Chakrabarty 2007) are not able to provide a precise determination of the pattern speed, as the authors of such models recognize; they usually ‘adopt’ spiral pattern speeds in the range $20-30$ km s$^{-1}$ kpc$^{-1}$ (30–40 km s$^{-1}$ kpc$^{-1}$ in the case of Rodríguez-Fernandez & Combes). Minchev & Quillen (2008) predict that the large-scale velocity surveys that are planned will be able to constrain the Galactic parameters, including the pattern speed, in the near future.

There are, however, theoretical arguments and numerical simulations telling us that we should expect a minimum of gas density at corotation. The effect of the corotation can be understood as follows: the dynamics of the gas in the potential perturbation of the spiral arms is such that it produces a net flow towards the centre inside the corotation radius, and a net flow towards the external parts of the disc, beyond corotation, resulting in a pumping out of the gas from the corotation region. Lacey & Fall (1985) proposed an analytical expression for the gas flow velocity on both sides of the resonance. Numerical hydrodynamic simulations were performed by Mishurov (2007) in 3D and by Lépine et al. (2001) in 2D.

Our renewed interest in the study of the H I circular gap is related to several consequences of its existence, as follows. First, because the corotation resonance is one of the fundamental parameters of spiral galaxies (e.g. Canzian 1998), its location in the Milky Way is of particular interest. The existence of the gap is important for confirming our understanding of the gas dynamics associated with the spiral structure of our Galaxy. The gap could also, in principle, permit us to infer a minimum ‘age’ of the spiral pattern, and contribute to the debate on the transient nature of the spiral structure.

The gap, if it is confirmed, could possibly explain the minimum in the rotation curve at a slightly larger Galactic radius (see, for example, a description of the minimum by Lépine et al. 2008). Indeed, as the rotation curve in the solar vicinity is almost completely explained by the matter contained in the disc (e.g. Lépine & Leroy 2000), in the presence of a gap, a Keplerian-like decrease of the rotation curve until the end of the gap would be expected. Furthermore, the gap and the radial flow of gas in opposite directions inside and outside corotation could be of great importance for models of chemical evolution of the disc, aimed at explaining the fine details of the gradient of metallicity. The gap could in some way make the exchange of metals in the interstellar medium across the gap less efficient.

As an example of such fine structure in the gradient of metal abundance, Andrievsky et al. (2004) in a study of the metallicity of Cepheids as a function of Galactic radius found an abrupt reduction in the metallicity between 10 and 11 kpc, assuming $R_0 = 7.9$ kpc. A similar step-like distribution was found by Twarog, Ashman & Anthony-Twarog (1997) in a study of the metallicity of open clusters.

In this paper, we use a kinematic distance method to estimate the distance from the Sun of the minima of H I density along the line of sight, for a large number of equally spaced longitudes, so as to produce a map of the location of the minima in the Galactic plane. The method is based on the hypothesis of circular rotation of the gas. We make use of recently published data from the LAB$^1$ Survey to perform a systematic analysis of the H I data, which covers both hemispheres with uniform calibration.

The paper is organized as follows. Section 2 presents the data from the LAB Survey used in the present work. Section 3 presents our method of analysis of the H I spectra and for mapping the regions with the lowest H I density. Section 4 presents a discussion of the evidence for the existence of the ring-shaped gap from other tracers, and Section 5 provides a short discussion of the existence of similar features in other galaxies. Some of the consequences for the spiral pattern of our Galaxy are discussed in Section 6. The conclusions and final remarks are presented in Section 7.

2 THE H I DATA

Recently, Kalberla et al. (2005) published the LAB Survey, which contains the final data release of observations of 21-cm emission from Galactic neutral hydrogen over the entire sky, merging the Leiden/Dwingeloo Survey (LDS: Hartmann & Burton 1997) of the sky north of $-30^\circ$ with the Instituto Argentino de Radioastronomía Survey (IAR: Arnal et al. 2000; Bajaja et al. 2005) of the sky south of $-25^\circ$. The angular resolution of the combined material is HPBW (half-power beam width) $\sim 0.6$. One of the improvements of these new data with respect to previous surveys is the introduction of corrections for the stray radiation.

The LAB Survey has been extensively used in several applications, as noted by Bajaja et al. (2005), Kalberla et al. (2005), Haud & Kalberla (2007) and Kalberla & Haud (2006), among others. In the present paper, we employ the H I data from the LAB Survey. These data cover Galactic longitudes from 0° to 360° and Galactic latitudes from $-90^\circ$ to $90^\circ$; for both coordinates the interval is 0.5 and the velocity resolution is 1 km s$^{-1}$. The spectra are presented in units of antenna temperature versus velocity. The data are stored in 720 ($b, v$) fits file maps at longitude intervals of 0.5.

3 ANALYSIS OF THE SPECTRA AND DISCUSSION OF THE EXISTENCE OF THE GAP

We analysed the H I spectra of the whole Galactic longitude range in steps of 0.5, with Galactic latitudes in steps of 1° in the range $\pm 5^\circ$, plus the additional latitudes $\pm 10^\circ$. In each spectrum we detected the velocity of the deep minima that are present, simply by identifying the channel with the lowest value of antenna temperature. Before this analysis we smoothed the spectra by replacing the temperature in each channel by the average of five channels.

Fig. 1 illustrates what we call a deep minimum. It shows the H I spectra for six directions, all at $b = 0.0$, except for the last frame. The vertical lines represent the detected locations of the minima. For instance, the H I spectrum obtained at $\ell = 240.0$ presents a clear gap at $v = 35$ km s$^{-1}$; this gap is so prominent that it seems to divide the spectrum into two independent regions. As a working definition, we consider that a ‘gap’ or a ‘deep minimum’ must be a minimum in the spectrum at which the antenna temperature is lower than 15 K and that is situated between regions of the spectrum with antenna temperatures at least 20 K above the minimum. In this way we consider only minima that are significant in terms of signal-to-noise ratio and that are not at the edges of the H I distribution, where the density becomes naturally low. We also considered separately the ‘not very deep’ gaps, with minima in the range 15 to 30 K, but also with edges reaching at least 20 K higher than the minimum. In some cases there is more than one gap in a given spectrum. One

$^1$ Leiden/Argentina/Bonn
example is the spectrum at $\ell = 80\,^\circ$, which shows two minima that are not very deep.

Usually, for a given longitude, a gap can be seen at the same velocity in spectra obtained at different latitudes, but it disappears at $b = \pm 10\,^\circ$. It is also the case, however, that in a number of directions the gap is not prominent at $b = 0\,^\circ$, but is easily seen at some other latitude $|b| \leq 5\,^\circ$. For instance, at longitude $\ell = 340\,^\circ$, there is no deep minimum at $b = 0\,^\circ$, but an almost good minimum can be seen at $b = -1\,^\circ$ (last frame of Fig. 1). This is not taken into account in the following statistics because it does not fulfill the condition of having emission higher than 20 K above the minimum on both sides. Because we want to illustrate in Fig. 1 not just the best cases, we present in the $\ell = 280\,^\circ$ frame a spectrum which does not fit perfectly the model that we advocate in the following sections. The minimum at 70 km s$^{-1}$ is a deep one, according to our definition. However, the minimum which would best fit our model is the one at 20 km s$^{-1}$, which is not deep. Nevertheless, the minimum at 20 km s$^{-1}$ is present and is deep at the same longitude but other latitudes, such as $b = 1\,^\circ$ and $b = -3\,^\circ$, so that it appears in the list of minima for $\ell = 280\,^\circ$. All measurements that show a deep minimum or a ‘not very deep’ minimum as we have defined them are considered in the following discussion.

The result of the first step of analysis discussed above is a catalogue of velocities of deep minima and of not very deep minima as a function of longitude. We present in Fig. 2 the $\ell$–$v$ diagram of these minima. The dashed line represents the locus in the $\ell$–$v$ diagram of the points situated on a circle of radius 8.3 kpc around the Galactic Centre, in the Galactic plane, as discussed later in greater detail. The line segments along the longitude axis at zero velocity represent the ‘forbidden regions’, or ranges of longitudes in which we would not see the effect of a ring-shaped gap in the HI distribution even if it were physically present. For instance, in the directions 0$^\circ$ and 180$^\circ$, the gas that rotates with the Galactic disc is supposed to cross the line of sight at right angles, and therefore to contribute only to a narrow region around $v = 0$ km s$^{-1}$ in the spectra. The reason why the directions 90$^\circ$ and 270$^\circ$ are also partially forbidden is more subtle. This can be seen from one of the classical Oort formulae,

$$V_r = Ad \sin(2\ell),$$

(1)

where $V_r$ is the radial velocity for an object situated at a distance $d$ in the direction $\ell$, and $A$ is Oort’s constant. This expression is valid for distances from the Sun that are not too large (smaller than about 2 kpc, say). This expression tells us that the velocity is zero also for 90$^\circ$ and 270$^\circ$. In other words, all the emission from the gas situated up to about 2 kpc contributes to a narrow

Figure 1. HI spectra for six different longitudes. The longitudes are indicated in the panels and are all at $b = 0\,^\circ$ except for $\ell = 340\,^\circ$, which is at $b = 1\,^\circ$. The vertical thick lines represent the locations of the deep minima. The intensities are in units of antenna temperatures (K).

Figure 2. The longitude–velocity diagram of the ‘deep’ minima and ‘not very deep’ minima observed in the spectra. The horizontal axis is Galactic longitude in degrees, and the vertical axis is velocity in km s$^{-1}$. The deep minima are shown in black; other gaps with a minimum in the range 15–30 K (see text) are shown in orange. The blue dashed line corresponds to a circle of radius 8.3 kpc in the Galactic plane. The line segments along the longitude axis represent the longitude ranges in which the minima would not be seen even if the ring-shaped gap existed along the whole circle.
velocity range in the spectrum, around \( v = 0 \) km s\(^{-1}\). Gas clouds situated at larger distances in those directions, however, contribute to non-zero velocities. If we exclude the ‘forbidden’ regions, about \( \pm 20^\circ \) around the directions 0° and 180° and \( \pm 10^\circ \) around 90° and 270°, and if we take into account the ‘not very deep’ minima, then we can see that the gap is present along the dashed line in about 90 per cent of the permitted longitude range. In the next section we conclude that the ring-shaped gap has a radius of approximately 8.3 kpc, which makes it more distant than 2 kpc in the directions 90° and 270°. We thus understand why we can see the gap in those directions too.

The question that we address next is why the gap is not well seen in 100 per cent of the ‘permitted’ longitude range (the whole longitude range excluding the directions close to 0° or 360°, and 180°). The minimum is not observed in a spectrum if there is a region along the line of sight containing gas with the same velocity as the gap. The velocity overlap is often only partial. We remark that when we are less rigorous in the definition of a gap; that is, when we consider that the minimum can be larger than 15 K (the ‘not very deep minima’) the longitude range covered is greater. For instance, the gap is very clear at \( \ell = 150^\circ \) at the velocity \( \sim -18 \) km s\(^{-1}\), where it is expected, but the antenna temperature at the minimum is 20 K (the spectra of selected directions can be easily obtained from the site of the LAB Survey\(^2\)). At \( \ell = 160^\circ \) there is still a minimum at \( v = -10 \) km s\(^{-1}\), but it is much less prominent, the temperature at minimum being 39 K. Similarly, at \( \ell = 210^\circ \) there is a minimum at the expected velocity, \( v = 20 \) km s\(^{-1}\), but the temperature at minimum is also 39 K. Those minima are not taken into account.

The more extended longitude range for which the gap (as we defined it) is only weakly observed (but still present), although it is a ‘permitted’ range, is 200–220°. A possible explanation is the following. There is a spiral arm passing relatively close to the Sun (at about 2 kpc in the direction of the anticentre; see, for example, Russell 2003). Because the distance of the gap that we are investigating is about 1 kpc from the Sun towards the anticentre, the distance between the gap and the arm is of the order of 1 kpc. The slope of the curve of radial velocity as a function of distance along the line of sight, for \( \ell = 210^\circ \) (in the middle of the longitude range that we are considering), tells us that a distance interval of 1 kpc produces a difference of velocity of the order of 10 km s\(^{-1}\). On the other hand, the peaks seen in the spectra at any longitude never have width smaller than about 10 km s\(^{-1}\). This is a minimum width of the H\( _1 \) emission associated with spiral arms, attributed to the turbulent motion of the gas. Therefore, it is not surprising that the minima in the spectra that are associated with the ring-like density gap are partially filled with emission that originates in a nearby region along the line of sight.

3.1 Detailed description of the gap

The kinematic distance of the gap from the Sun can be easily estimated, as there is no distance ambiguity, because the gap is situated outside the solar circle, where there is only one kinematic solution. Furthermore, the distance obtained depends very little on the adopted rotation curve, as the gap is close to the solar circle. It must be remembered that if the gap were coincident with the solar circle, its velocity as seen from the local standard of rest would be zero at all longitudes independently of the rotation curve.

In the present work, we used a relatively flat rotation curve, conveniently fitted by exponentials and a Gaussian (units are km\(^{-1}\) and kpc):

\[
V = 245 \exp[-r/75.0 - (3.6/r)^2] + 350 \exp[-r/3.3 - 0.1/r] - 20 \exp[-(r - 8.8)/(0.8)^2].
\]  

(2)

The curve is presented in Fig. 3, where the points represent the CO data obtained by Clemens (1985) corrected for \( R_0 = 7.5 \) kpc and \( V_0 = 210 \) km s\(^{-1}\). This curve is close to that derived by Fich, Blitz & Stark (1989), and the fitted expression is similar to one previously used by our group (e.g. Lépine et al. 2008).

The distribution of the density minima in the Galactic plane, derived from their kinematic distances from the Sun, is shown in Fig. 4. The minima observed at different latitudes are all projected onto the Galactic plane. The ring-shaped gap is circular and very clear. It looks like the Cassini division in Saturn’s rings. Although

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\( ^2 \) http://www.astro.uni-bonn.de/~webaiub/english/tools_labsurvey.php

Figure 3. The rotation curve of the Galaxy for \( R_0 = 7.5 \) kpc. The line is a fit to the CO data, using the empirical expression of equation (2).

Figure 4. The distribution of the gaps in the Galactic plane. The Galactic Centre is at the position (0,0) and the Sun is at (0,7.5); the units are kpc. The solar circle with radius 7.5 kpc is shown. Gaps belonging to the Galactic Cassini-like division are represented by filled circles – in blue if they are ‘deep’ gaps, and in black if their minimum is larger than 15 K. The gaps situated outside the ring are shown with + signs – in red if they are ‘deep’ and in orange if they are ‘not very deep’.
minor changes in the Galactic radii of the gaps appear in experiments with different rotation curves, the ring-shaped aspect of their Galactic distribution remains unchanged. The histogram of the Galactic radii is shown in Fig. 5. Most of the structures not belonging to the ring have the shape of spiral arms and can be understood as inter-arm gaps. The prominent one at about 11 kpc to the left of the centre in the figure seems to be on the external side of the Carina-Sagittarius arm. Taking into account the different Galactic scales adopted in the two works, it coincides with an inter-arm region previously observed by Levine, Blitz & Heiles (2006) at 13 kpc to the left of the centre. Fig. 4 tells us that the ring-shaped gap cannot be explained as a combination of inter-arm gaps, nor is it a local structure seen only close to the Sun.

It does not seem likely that the traditional approximation of circular orbits adopted in calculations of kinematic distances, instead of orbits that take into account the influence of the Galactic bar, will have a strong effect on the shape of the ring. The part of the Galactic plane that is of interest in the present study is situated outside the solar circle. For instance, in the study of the kinematic response of the outer stellar disc to a central bar, Mihlbauer & Dehnen (2003) predicted that the bar-induced radial and azimuthal motion of the LSR should be very small (at most a few kilometres per second).

We estimated the average width of the gap by measuring the velocities of each edge of the deep minima in the spectra. The profiles of the minima often depart from Gaussian fits, because there are flat minima. Instead, we just added 20 K to the antenna temperature of the lowest point, and determined where this threshold line intersected the edges of the line profile. The exact value of the threshold is not important, as the edges are usually sharp. The two velocities obtained in this way were transformed into distances from the Sun using the kinematic distance method. The line segment defined by the two distances was then projected onto the local radial direction.

We found an average width of 0.8 kpc, with values in the range 0.5 to 1.3 kpc.

The H I density in the gap can be roughly estimated from the classical expression connecting the column density $N_H$ with the product of antenna temperature $T$ and velocity interval $\Delta V$ (e.g. Vershur 1974): $N_H = 1.82 \times 10^{18} T \Delta V (N_H$ in units of cm$^{-2}$, with $T$ in units of K and $\Delta V$ in km s$^{-1}$). Selecting a number of cases for which $T$ is smaller than 5 K over an interval of velocity of 20 km s$^{-1}$, with a corresponding length along the line of sight of about 1 kpc, the resulting density is quite low, of the order of 0.05 cm$^{-3}$. The average density in regions close to the ring-like gap, in a smoothed distribution that does not consider the gap, is about 0.3 cm$^{-3}$ (e.g. Amôres & Lépine 2005), which means a factor of 6 in density contrast between the gap and the surrounding regions.

4 THE GAP SEEN WITH OTHER TRACERS

Although the hydrodynamical forces that produce a gas flow that diverges from the corotation radius do not act on stars, it is expected that the low gas density in the gap inhibits star formation, and a lower density of young stars should be observed. This is indeed the case, as can be seen from the histograms of galactocentric distances of open clusters and of Cepheids shown in Fig. 6. The open clusters were taken from the New Catalogue of Optically Visible Open Clusters and Candidates of Dias et al. (2002). We selected from this catalogue the clusters that have known distances, in the age range 2 to 40 Myr. The Cepheids were taken from the catalogue of Berdnikov et al. (2003); the complete sample of 440 stars was used. It should be noted that the two types of objects have their distances estimated by different methods (main-sequence fitting and period–luminosity relation), and different from the kinematic distance method used for H I, so that they can be considered as independent measurements of the gap radius.

In principle, the completeness of any sample of stars decreases with distance from the Sun, as distant stars are more difficult to observe. For instance, the sample of visible Mira variables is uniformly distributed around $R_0$. This happens because as the distance to the Sun increases in the inward and outward directions, other effects in addition to distance, such as the greater extinction towards the Galactic Centre and the exponential decrease of the stellar density with Galactic radius, certainly have an influence on the apparent density of a given type of object as a function of distance. But these are smooth effects, unable to produce a break in the distribution. A comparison of the histograms with symmetric curves centred on the position of the Sun reveals an abrupt decrease of the density from

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3 Available from http://astro.iag.usp.br/~wilson
7.5 to 8.0 kpc. We believe that the star formation rate is almost zero in the gap. The stars and open clusters that are formed just outside the gap have typical perturbation velocities of about 10 km s\(^{-1}\) with respect to the local rotation curve when they start their epicyclic motion around the circular orbit (see Lépine et al. 2008 for a detailed description of this process). As a consequence, they partially fill the gap in about 70 Myr, half the epicycle period. It should be noted that the Cepheids have typical ages older than this. It is therefore not surprising that the gap is not more prominent using these two tracers. For older stars the gap is completely smoothed out, as the corotation resonance scatters the stellar orbits (Lépine, Acharova & Mishurov 2003). Of course, one could interpret the histograms of Fig. 6 as showing a peak at about 7 kpc, instead of a density decrease around 8 kpc. At least, however, the above discussion shows that there is no conflict between the hydrogen density gap and the distribution of young stellar tracers.

Concerning other young tracers, it is well known that H\(_\text{II}\) regions, as well as molecular clouds observed in CO, are strongly concentrated in the spiral arms. One difficulty is that in order to see the ring-shaped gap clearly it is necessary to observe minima along a large fraction of the gap-ring, and this is not possible for objects that are restricted to the spiral arms. Another problem is how to distinguish an inter-arm region from the ring-shaped gap. Paladini, Davies & DeZotti (2004) present a histogram of galactocentric distances of H\(_\text{II}\) regions in their fig. 3. The histogram shows a minimum at about 8.5 kpc, but this is the result of a selection effect, as the authors removed from their sample all objects situated along the solar circle (velocities with modulus less than 10 km s\(^{-1}\)). A re-analysis of the distribution of H\(_\text{II}\) regions in the Galaxy is beyond the scope of the present work.

5 RING-SHAPED GAPS IN OTHER GALAXIES

Are H\(_\text{I}\) ring-shaped gaps seen in other galaxies as well? In the literature the emphasis is more often given to ring-shaped H\(_\text{I}\) emission. There are emission rings that are obviously produced by the interaction of colliding galaxies, as they present large angles with respect to the plane of the host galaxy. However, there are also many external rings situated in the plane of galactic discs. In these cases, what looks like an external ring could be a consequence of the existence of a gap that separates the ring from the main H\(_\text{I}\) distribution. A very rough statistical analysis can be made using, for instance, the unbiased H\(_\text{I}\) and optical study of 16 nearby northern spiral galaxies by Wevers, van der Kruit & Allen (1986), as the radial profiles of H\(_\text{I}\) are given in that work. In many cases (NGC 2903, 3726, 4203, 4258, 4725, 5055), the H\(_\text{I}\) density profile presents a minimum that separates a faint outer ring. This is an indication that ring-shaped H\(_\text{I}\) gaps are not rare.

The question of the connection between a gap and corotation is more difficult to investigate, as the corotation radius has been determined only for a limited number of galaxies, and there are often conflicting determinations from different methods. For two of the galaxies of the list given above there is a corotation radius estimated by Vila-Costas & Edmunds (1992). One is NGC 2903, with \(R_c = 2.3\) arcmin, and the gap, as shown by Wevers et al., is wide and begins at about 2.8 arcmin (but using a beamwidth smoothing of 0.5 arcmin). The other is NGC 5055, with \(R_c = 3.1\) arcmin, but the gap starts at about 6.6 arcmin. In this case the corotation seems to be excluded as the cause of the gap. As examples of the gap–corotation association, Schommer & Sullivan (1976) state that this happens in NGC 4736. In the study of the molecular gas distribution over M83 by Lundgren et al. (2004) a ring can be seen where the gas is depleted very near the corotation circle outside the inner arms (see, for example, their figs 5 and 14), although the authors do not explicitly note this feature.

6 CONSEQUENCES FOR THE SPIRAL STRUCTURE OF THE GALAXY

The existence of a ‘vacuum’ ring is certainly able to constrain models of the spiral arms of the Galaxy. We argued in the Introduction that there is a convergence of the direct methods of determining the corotation radius, telling us that corotation is close to the solar orbit. The mean radius of the ring is 8.3 kpc, which coincides with the corotation radius obtained by DL, and is within the measurement errors in several other papers based on direct observations. On the other hand, it is a prediction from both classical spiral wave theory and numerical hydrodynamic simulations that the spiral arms produce a vacuum around corotation. In this sense, the observation of the vacuum ring can be considered as an independent measurement of \(R_c\). The idea of the coexisting multiple pattern speed has been suggested by several authors (e.g. Rautiainen & Salo 1999; Minchev & Quillen 2006). These authors conclude that this is a possibility in real galaxies, but do not declare that it occurs in our Galaxy. The fact that we observe only one ring-like gap, and that this gap is a well-defined one, is an argument against the hypothesis of multiple pattern speeds in the Galaxy, which would produce multiple ring-like gaps or poorly-defined rings. It should be remembered that the self-consistent model of spiral structure proposed by AL (1997), which seems to present multiple structures, is based on the hypothesis of a single pattern speed. The results of AL were confirmed by Martos et al. (2004), with the same hypotheses and same conclusions. We avoid in the present work the discussion of the pattern speed of the bar, which might affect the internal regions of the Galaxy. There are arguments in favour of a different pattern speed for the bar (e.g. Dehnen 1999), and observations supporting this view (Debattista, Gerhard & Sevenster 2002), which challenge the traditional hypothesis that the extremities of the bar are connected to the arms and the two structures have the same rotation velocity.

Moving now to the question of the lifetime of the spiral pattern, what does the ring-like gap tells us about it? In contrast to the classical theory of spiral arms, according to Sellwood & Binney (2002) and Merrifield, Rand & Meidt (2006), among others, transient waves with a wide range of pattern speeds develop in rapid succession. If the gap has an average width of about 800 pc and the gas flow just outside the gap has a typical velocity of the order of 0.5–1 km s\(^{-1}\) (Lacey & Fall 1985; Mishurov, Lépine & Acharova 2002, hereafter MLA), and supposing that the gap had the same density as the neighbouring regions at the initial instant, it would take about 0.8 Gyr to pump out the gas to form the gap. This relatively short time would be the minimum age of the present spiral structure. This is not a strong restriction; the restrictions based on the metallicity gradient in the disc seem to be able to impose longer lifetimes. MLA adopted the idea that the star formation rate in the disc is proportional to \(|2 - \Omega_c|\), which is the velocity of the gas with respect to the spiral arms, or the rate at which the star-forming machine (the arms) is fed with gas. This function presents a minimum at corotation, and is able to explain positive slopes of metallicity beyond corotation. This interpretation can be combined with the results of Maciel, Costa & Uchida (2003), which show that planetary nebulae younger than 4 Gyr have a metallicity slope beyond corotation that is flat or even positive, and very different from that of the older planetary nebulae. This suggests that the present position...
of corotation was established about 3–4 Gyr ago, and that this is the age of the present spiral pattern.

7 CONCLUSIONS

There is strong evidence in favour of the existence of a ring-like gap in the distribution of H I in the Galactic disc, similar in appearance to the Cassini division in Saturn’s rings. Although the existence of the gap was known from the very first H I surveys, a detailed description of it has not been available until now. The mean radius is 8.3 kpc, for $R_0 = 7.5$ kpc, and its mean full width at half maximum is of the order of 0.8 kpc. It is a prediction from both spiral wave theory and numerical hydrodynamic simulations that the spiral arms produce a vacuum around corotation. The radius and width of the ring-shaped gap coincide precisely with the results of numerical hydrodynamic simulations performed by our group (Lépine et al. 2001) for the same value of $R_0$. The present result is therefore a confirmation of our understanding of the spiral density waves mechanism. It tends to favour the classical idea of a single pattern speed, as the ring-like gap is unique and reveals a single corotation radius. It also favours a relatively stable or long-lived spiral pattern, as in our interpretation of the chemical evolution of the disc.

ACKNOWLEDGMENTS

EBA received financial support for this work from FAPERJ (Fundação Carlos Chagas Filho de Amparo à Pesquisa do Estado do Rio de Janeiro, E-26/100.457/2008), CNPq (Conselho Nacional para o Desenvolvimento Científico e Tecnológico 150772/2008-4) and Fundação para a Ciência e Tecnologia (FCT) under the grant SFRH/BPD/42239/2007. We also thank the referee for the helpful comments.

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