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THE CAR–SGR ARM AS OUTLINED BY SUPERCLOUDS AND THE GRAND DESIGN OF THE GALAXY

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It is found that H I superclouds are regularly spaced along the very long Car–Sgr arm, the mutual distances being mostly 0.1 and 0.2 in units of the Solar distance to the centre. Such regularity is instrinsic to the grand design galaxies with density-wave spiral arms. A higher density of old stars and star clusters within the Car–Sgr arm is observed, implying a strong density wave. A symmetric second arm should exist in a grand design galaxy yet this arm is well seen only in the II quadrant, being behind the Per arm. The positions of most superclouds, the giant H II regions and GMCs over the Galaxy are compatible with a four-arm spiral structure with two less pronounced additional arms midway between the two principal arms; the nearby Per arm is one of the secondary arms. The pitch angle of such a grand design spiral pattern is 10°–12°. If this pattern does exist, the long segments of the arms have none the above-mentioned spiral-arm tracers. At any rate the Car–Sgr arm is certainly much brighter and more regular than all the others. The most probable arm class of the Galaxy is 9–12; it is multiarm or grand design galaxy.

KEY WORDS Galactic structure, ISM clouds

1 INTRODUCTION

The existence of the spiral structure in our Galaxy is well beyond doubt, yet its grand design is still controversial. The general agreement concerns only the positions of three local fragments of arms (Car–Sgr, Ori–Cyg and Per) and the Car–Sgr and the Per fragments are usually believed to be parts of long Galactic-scale arms. However, whether the Galaxy has two, three or four arms is still uncertain. Even the more fundamental issue on whether the Milky Way system has a spiral structure of the grand design or flocculent type is still unresolved. The regular symmetric arms in the grand design galaxies are generally considered to be connected with spiral density waves, whereas chaotic pieces of arms in the flocculent spirals are probably sheared very large regions of star formation (Elmegreen and Efremov, 1996).

We tried to approach the nature of the Milky Way spiral arms with data on the locations of H I superclouds in the I and IV quadrants of Galactic longitudes. These superclouds with characteristic masses of ten millions suns are the largest entities of interstellar matter and are located mainly within spiral arms being counterparts of stellar complexes and supergiant H II regions (Elmegreen and Elmegreen, 1983, hereafter EE83). These authors found that in a number of spiral galaxies the (supergiant) H II regions and superclouds form chains with regular spacing along the arms. Superclouds are surely the best tracers of spiral arms (Elmegreen, 1987), yet after the pioneering work of McGee and Milton (1964) who found a number of supergiant H I clouds in the outer Galaxy, superclouds have not been used in attempts to delineate the Galactic spiral arms.

We found that the superclouds outline the very long Car–Sgr arm even better than GMCs, and they are regularly spaced along it. We discuss this and other evidence that the arm is connected with a spiral density wave and that the Galaxy has a spiral structure of grand design character. The probable models of this structure are briefly discussed at the end of the paper.

2 THE CAR–SGR ARM AS OUTLINED BY SUPERCLOUDS

The existence of this long (about 40 kpc) arm with a pitch angle of 10° was suggested by Cohen *et al.* (1985) and Grabelsky *et al.* (1988) from the location of GMCs. Here we attempted to trace this arm with data on the H I superclouds, combining data for both the I and IV quadrants of galactic longitudes.

There exists a lot of evidence on close associations of H I concentrations with GMCs, e.g. the data of Elmegreen and Elmegreen (1987a) for the I quadrant and those of Digel *et al.* (1994) for the outer Galaxy. The latter authors noted that the GMCs are always within 40 pc of the centres of much larger H I concentrations. This is the case also for the superclouds within the Car arm where the GMCs appear to be located at the cores of much larger H I concentrations, as noted by Grabelsky *et al.* (1988).

Elmegreen and Elmegreen (1987a) obtained the distances, longitudes and masses (mainly around 10 million suns) for superclouds in the I quadrant. These authors noted that the closer to the centre, the larger is the contribution of molecular hydrogen to the total mass of a supercloud.

There are no direct data for superclouds within the IV quadrant, yet we believe they are outlined by closed contours of H I (with the GMCs near their centres) in the figures of Grabelsky *et al.* (1987). It is worth noting that the velocity ranges in these figures are small enough to delineate just the objects confined within the Car arm, as the CO and H II data for the same velocity ranges proved. Note also that the resolution beam was much smaller than the size of the closed contours that are evidence of H I superclouds within the Car arm.

With the data of authors we have compiled a map of the supercloud distribution along the Car–Sgr arm. Longitudes of centres of the H I superclouds in the Car

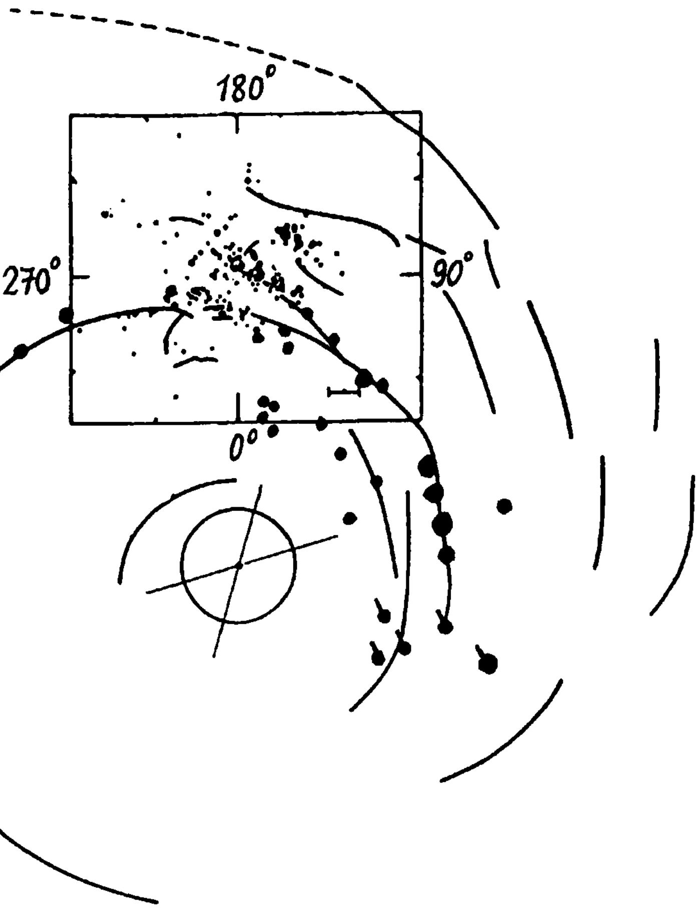

Figure 1 Positions of superclouds in the I quadrant (sizes are proportional to masses) and within the Car arm in the IV quadrant (sizes are arbitrary), superimposed on the H I ridges and the local distribution of young clusters and associations (after Weaver, 1970). Two extreme possible positions for the bar are also shown. Within the I quadrant the superclouds for which the distance may be uncertain (far distances being adopted) are marked with a tick.

arm were taken from Figure 15 of Grabelsky *et al.* (1987) and it was accepted that they are near the centres of superclouds in the *l,b* plane. These distances are taken from Table 2 of Grabelsky *et al.* (1988); they are mostly kinematical for the GMCs outside the solar ring and are the distances of connected H II regions for the nearby GMCs, so for the IV quadrant distances there is no ambiguity.

Thus a composite picture of locations of superclouds along the Car–Sgr arm was obtained, as shown in Figure 1. A preliminary version of this picture was published earlier (Efremov, 1995a). Note the quite good agreement of the supercloud Car–Sgr arm having a pitch angle of 10° (obtained from the distribution of GMCs by Grabelsky *et al.*, 1988) with the old picture of Weaver (1970), who found the angle

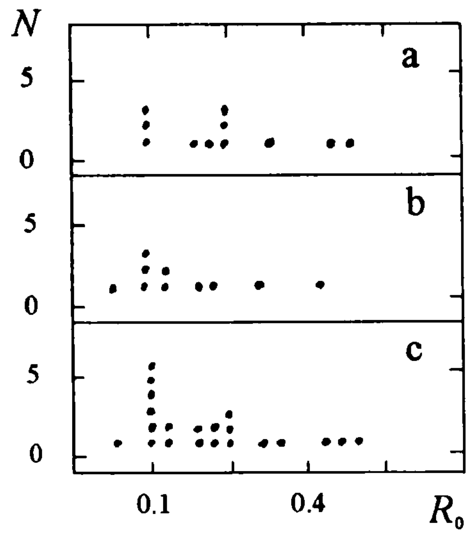

Figure 2 Distribution in spacing between adjacent superclouds along the Car–Sgr arm: (*a*) within the IV quadrant, the Car arm; (*b*) within the I quadrant, the Sgr arm; (*c*) combination of the two preceding pictures. Distances are given in units of the distance from the Sun to the Galactic centre.

to be 12°. For a few superclouds from the I quadrant with ambiguous distances we adopted the far ones (noted with a tick in Figure 1) and for three cases (just for positions along the arm) this option is justified since with these far distances these superclouds have giant molecular cloud counterparts (Figure 1). Superclouds with masses lower than two millions suns (masses from Table 2 of Elmegreen and Elmegreen, 1987a), all being at distances smaller than 3 kpc, were ommited from Figure 1.

This composite picture of superclouds in the I and IV quadrants shows the Car–Sgr arm to be as long as and more regular than that outlined by the GMCs (compare with Figure 4 in Grabelsky *et al.*, 1988), and, what is not revected by the distribution of GMCs along the arm, there is a striking regularity in the spacing of H I superclouds all along the arm, the preferred distances between adjacent superclouds being 0.1 and 0.2 of the distance from the Sun to the Galactic centre (Figure 2). We may therefore affirm that the Galaxy belongs to the class of spiral galaxies with regular spacing of superclouds (and therefore star complexes) along the arms.

3 THE ARM CLASS OF THE GALAXY

This conclusion involves certain implications concerning the spiral class Galaxy. A classification of spiral arms according to increasing level of regularity was proposed by Elmegreen and Elmegreen (1982). It included 12 classes of arms: clases 1–4 for flocculent spiral and 5–12 for regular (grand design) arms, class 12 being ascribed to galaxies with two long symmetric arms. Later, the barred spirals (classes 10–11) were omitted and galaxies of classes 5–9 were considered to be multiarmed (Elmegreen and Elmegreen, 1987b, 1989). This is clearly a distinction of fundamental significance, reflecting the different mechanisms of spiral structure formation. It is worthy noting that the flocculent galaxies are more numerous than the grand design ones, after taking into account the lower luminosity of the former.

There have been only a few previous attempts to evaluate the arm class of the Galaxy. Elmegreen (1985) concluded that it is 6–7 and the Milky Way is more or less a regular galaxy; she considered a number of optical and radio data over all the Galaxy.

Some evidence is provided by the existence of the very long Car–Sgr spiral arm outlined by GMCs and H I superclouds. This may be connected with the arm class via the dust class, a good corvelation being found between (Efremov, 1989). The dust classes 1–5 were introduced by Lynds (1980) as an angular measure of the dust lane lengths in spiral galaxies, class 5 being for a lane length greater than or equal to 180°. We assumed that the chain of GMCs and H I superclouds along the Car–Sgr arm must be seen from outside as a dark lane and noted that the angle at the Galactic centre between the end points of this arm is clearly larger than 180° (not 120° as we supposed earlier in Efremov, 1989). This implies that the Galaxy dust class is 5 and from Figure 33 in Efremov (1989) the most probable arm class 12 or 9 follows.

Recently Vallee (1995) also noted that the existence of the long Car–Sgr arm gives a clue to certain arm classes of the Galaxy. He believed that the Milky Way class is AC 9 if there is internal symmetry, otherwise it could be AC 3.

Now we noted that in the list of 22 galaxies with regular H II strings given by Elmegreen and Elmegreen (1983), 18 have the arm class in Elmegreen and Elmegreen (1987a) and of those galaxies seven are of AC 9, and five are of AC 12. Both classes 9 and 12 imply the presence of two symmetric spirals, long ones for AC 12 and with additional multiple, long and continuous outer spirals for AC 9. This comparison with other galaxies is consistent with the high (13:18) probability that the Galaxy is of multiarm or grand design type and we conclude that the Galaxy arm class is more probably 9. (In fact the existence of a bar in the Galaxy implies the formal class 10 or 11, yet we discuss here the degree of regularity of the spiral pattern which is observed to be rather different within the class of barred galaxies.)

4 THE CAR–SGR DENSITY-WAVE SPIRAL ARM

This classification is consistent with the usual assumption that the Galaxy's spiral structure is connected with spiral density waves. Moreover, the dust class 5 implies a strong density wave, as was found by Lynds (1980). At any rate this should be the case for the Car–Sgr arm, as different pieces of evidence proved. First, there are characteristic deviations from the circular velocities in the motions of high-luminosity stars within the arm, which confirm its density-wave nature (e.g. Gerasimenko, 1993).

This arm includes at least 13 regularly spaced superclouds, more than in any arm in EE83's list of 22 galaxies. The only realistic explanation of the regular spacing of superclouds along an arm seems to be a result of gravitational instability along the density-wave arm, owing to the enhanced gas density and lower shearing within such an arm (EE83, Elmegreen, 1994).

A third piece of evidence is provided by the recent data on the enhanced density of the old disc stars within the Sgr arm. According to Paczynski *et al.* (1994), at distance of some 2 kpc in the field $l = 1°$, $b = -3.9°$ there is an excess in the number of stars (with Mv as low as +7, and therefore old stars) by a factor of ~ 2. We consider this to be the signature of a strong density wave in the old stellar disc.

In fact, there is increasing evidence that the spiral density waves are often strong enough and are seen also in the old disc populations. Flocculent galaxies have no or little old-star density enhancements within their fragmented arms, whereas grand design galaxies have, as was proved by Elmegreen and Elmegreen (1984) for many galaxies. This finding was confirmed with the higher resolution near-IR data for M83 (Adamson *et al.*, 1987) and more recently for M51 (Rix and Rieke, 1993; Rix and Zaritsky, 1995) and M99 (Gonzales and Graham, 1996). These authors confirmed that the red light comes from the old red giants and not the young supergiants, the respective density enhancement within an arm being as large as 2 or 3. Also it has long been known that in M31 the clusters of all ages concentrate in the wide spiral arms (Hodge, 1979) which most probably are connected with the density waves (Efremov, 1989).

The old clusters should also concentrate in the Car–Sgr arm as old stars seemingly do, yet there is the long-standing general opinion that in the Solar neighbourhood only open clusters younger than some 30 Myrs concentrate in the spiral arms (Becker, 1963; Lynga, 1987). However, this opinion is not true for the Car–Sgr arm. It is explained mostly with the observational selection against discovery as well as with unreliable distance determinations for more distant older clusters. We have found recently that within a distance of 1.4 kpc, the density of open clusters and Cepheids inside the Car–Sgr arm is about the same as outside this arm (and within the Local arm) for the age range 3–12 Myr (73 objects), whereas for the age range 50–100 Myrs (115 objects) the density inside the arm is twice that outside it (Efremov, 1997).

The older clusters show weak or no concentration in the Cyg–Ori (Local) arm, within which the Sun is located, because this arm is a spur (Weaver, 1970), evidently connected with star formation, and is not a density-wave arm (Elmegreen and Efremov, 1996).

A high density of older clusters was observed in the fragment of the Car–Sgr arm within the longitude interval of some 300°–330°, and most of it is within 1.4 kpc distance. The density of older clusters is essentially higher there than outside this fragment along the arm and it is considered to be an older complex (densignated as complex C in Avedisova 1987, 1989). This position also locates a complex of older

Cepheids (Berdnikov and Efremov, 1993; Efremov, 1994). A giant clump of A stars was found by Bok (1964) many years ago at about the same position too.

However, observational selection effects should be investigated, especially for clusters, before certain conclusions could be obtained. It is possible that only in this near (and rather clean) part of the Car–Sgr arm are we able to see older objects and call this fragment an old complex, whereas the real density of these objects is more or less uniform along the arm (Efremov, 1995a, 1997). At any rate, we may affirm even now that older clusters (and stars) do concentrate at least in a segment of the Car–Sgr arm. Cepheids with ages up to 80 Myr surely concentrate along this arm only (Berdnikov and Efremov, 1993).

5 THE SPACING OF SUPERCLOUDS/STAR COMPLEXES IN THE CAR–SGR ARM

According to the theory (Elmegreen, 1994), the spacing should be about three times an arm width between the complexes, and the data of EE83 is consistent with this conclusion. It is seen in Figure 2 that the preferred distances between superclouds are 0.1 and 0.2 of R_0, the distance from the Sun to the Galactic centre (we will write for brevity 1 and 2 kpc) and they scale directly with R_0. The distances between the centres of superclouds were measured separately for the I and IV quadrant segments of the arm. Assuming the most reliable distance to the Galactic centre to be 7.1 kpc (both from globular clusters, Rastorguev *et al.* 1994, and from Cepheids, Dambis *et al.* 1995), these spacings are 0.7 and 1.4 kpc. The width of this arm, as outlined by the high-luminosity stars in the Solar vicinity, is about 1 kpc (Gerasimenko, 1993). Hammersley *et al.* (1994) noted from their IR data that the width of the Sct stellar arm is about 300 pc; evidently this is the value for older stars. Anyway it is necessary to decide first which distance, $0.1R_0$ or $0.2R_0$, is the fundamental one to be compared with the theoretical result.

It is worth noting at this point that H I superclouds are the progenitors of vast star complexes and these entities are observable at different stages of evolution with different proportions of gas and stars of different ages (up to 100 Myrs) inside them (Elmegreen and Elmegreen, 1983; Efremov 1989, 1995a,b). The optical data for the Solar vicinity show that the most massive star complexes (outlined by Cepheids and star clusters) concentrate just within the local segment of the Car–Sgr arm and this is one more reason to consider it to be part of a Galactic-scale spiral arm (Efremov, 1994).

In the Solar neighbourhood the Cepheid complexes along the Car–Sgr arm are separated by some 1 kpc distance (Berdnikov and Efremov, 1993) whereas two complexes of young clusters in the same arm are at a distance of 2.4 kpc, being for unknown reasons below the mean galactic plane (Alfaro *et al.*, 1992). Between these young complexes there is one delineated with older clusters and Cepheids, and there is a supposition (Avedisova, 1989) that young and older complexes possibly alternate along an arm. The Cepheid age range is just suffiently large to outline the complexes of different ages (excepting rare very young complexes involved in the burst of O star formation and classified as superassociations, Efremov, 1995b) and the distance of some 1 kpc between complexes outlined by Cepheids probably means that this is the basic spacing. On the other hands, as was discussed in Section 3, the density of older objects is more probably informly high along the arm and the apparent old complex is simply a result of the visibility conditions.

It is worth noting that all of the four largest superclouds, with masses in excess of 20 million suns (Elmegreen and Elmegreen, 1987) are aligned along the Sgr arm and are at a distance of about 1 kpc from each other (Figure 1). This fact proves that there is no regular alternation of young and older complexes along an arm. It looks as if the intrinsic spacing is in fact about 1 kpc, yet in some positions superclouds/young complexes were missing. Note, however, that these four superclouds are in the inner Galaxy where the average gas density is higher.

The average distance between H I superclouds in the outer Galaxy is 2.4 kpc (EE83), but it should be 2.3 kpc if the Galaxy obeys the relation found by EE83 between supercloud spacing and galaxy size (Alfaro *et al.*, 1992). The spacing, being the Jeans's wavelength, may well be smaller where the gas density is higher and there are signs of this also in Figure 2*a*, mostly for the outer Galaxy, comparing with Figure 2*b* for the inner Galaxy. We have found the same situation in two galaxies of EE83's list (NGC 1365 and NGC 2395): the larger the distance from the centre, the larger is the spacing of the giant H II regions.

Bimodal distribution in spacings between superclouds seems to be rather usual. Elmegreen and Elmegreen (1983) noted that among galaxies with regular strings of (supergiant) H II regions "the separation of one of the adjacent pairs of bright H II regions along a string was nearly twice that of other pairs in the same string, as if a single H II region were missing from the middle of a more continuous string. For each of these cases, a faint H II region could still be detected at the expected intermediate position". Note that between some superclouds within the Car arm which are at double spacing there are sometimes GMCs (Figure 3). EE83 data for one more galaxy, NGC 613, also displays a bimodal distribution (just around 1 and 2 kpc) for spacings of the (supergiant) H II regions in the main arm. This bimodality needs to be explained by the theory.

6 THE GRAND DESIGN OF THE GALAXY

6.1 Models of the Galactic Spiral Pattern

The overall review of the Galaxy spiral structure, given by Elmegreen (1985), is not yet out of date, though important new evidence has appeared now for the existence of the small bar. These is no general agreement about the bar size or the position angle, though its existence seems to be well established from a number of observations, such as kinematical data on gas (Binney *et al.*, 1991; Wada *et al.*, 1994), unresolved IR stellar data (Blitz and Spergel, 1991; Blitz *et al.*, 1993), and star counts from the Two-micron Galactic Survey (Hammersley *et al.*, 1994; Calbet *et al.*, 1996).

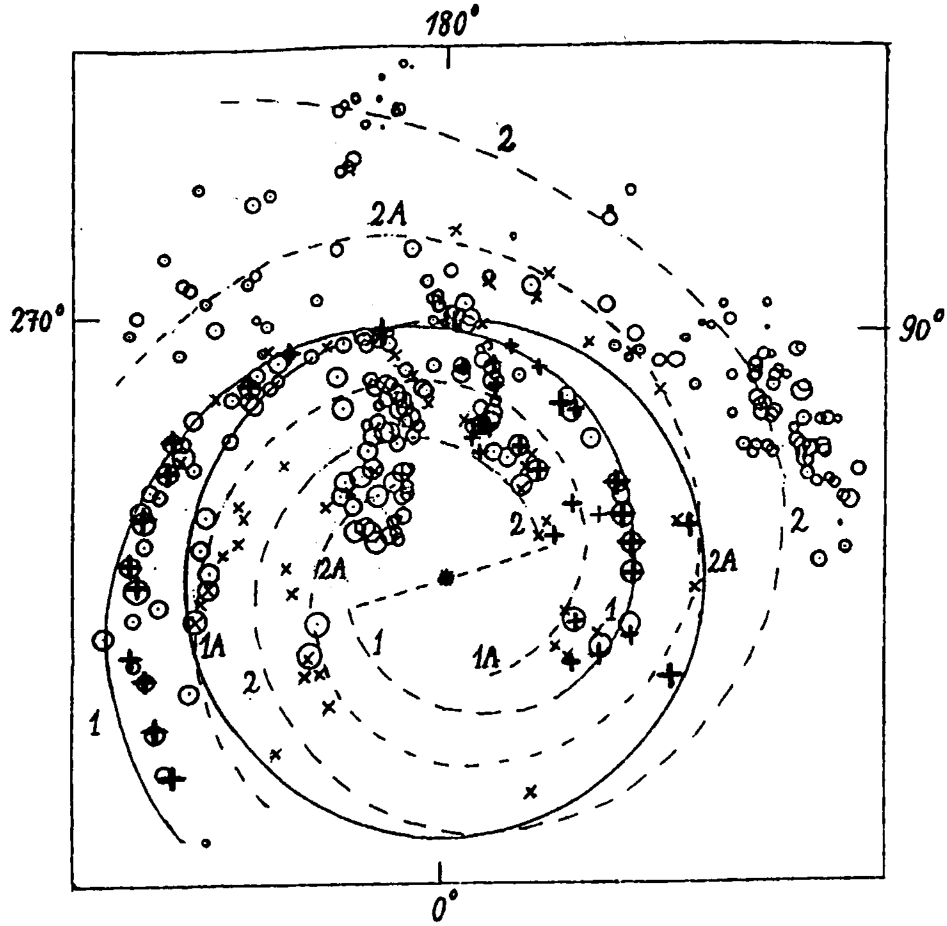

Figure 3 A composite sketch of the distribution of superclouds (from Figure 1, shown as crosses "+"), GMCs (Bronfman, 1992, shown as circles) and giant H II regions (Georgelin and Georgelin, 1976, multiple signs "x"). The position of the Car–Sgr arm (denoted 1) with a pitch angle of 10° is shown, together with the possible second symmetric arm (2) and two more additional arms (1A and 2A), obtained from 1 and 2 by turning through 90°. The Solar ring and the possible position of the bar (adopted from Hammersley *et al.*, 1994) are also shown. The sizes of GMCs circles are proportional to their masses.

The popular map of the spiral structure by Georgelin and Georgelin (1976) is based on an extensive set of H II region distances (including the kinematical ones). It shows the four-arm (yet not symmetrical) structure and one of the arms fits rather well with the Car arm, but not its Sgr part. However, it was shown by Bash (1981) that after taking account of non-circular motions connected with the spiral density waves these data are compatible with the two-arm pattern.

Kulkarni *et al.* (1982) obtained four spiral arms with a pitch angle of 22°–27° using a rising rotation curve. Petrovskaya (1987) prefers a four-arm structure with a pitch angle of 14°, using the distribution of H I obtained from the kinematical data; later (Malakhova and Petrovskaya, 1992) an angle of 18° was suggested.

Other models of the Galactic spiral structure present a two-arm pattern. Hammersley *et al.* (1994) propose a two-arm model which includes the bar, based on star counts from the two-micron Galactic Survey. The model is consistent with the forms of the major features in the 2.2 micron surface brightness map within longitudes 10°–40° at both sides of the centre of the Galaxy. The essential detail of this model is a region of intensive star formation at longitude 27°, most probably associated with the nearby end of the bar. It is oriented at an angle of 75° to the direction to the Galactic centre and has length about 4 kpc from the centre. Other models, especially kinematical models (Blitz *et al.* 1993, Wada *et al.* 1994) lead to a shorter bar and smaller angle between it and the Sun–Galactic centre line. Possible reasons for this discrepancy are discussed by Calbet *et al.* (1996).

A two-arm spiral structure was obtained by Han and Qiao (1994) for the regular magnetic field of the Galaxy. After studying the rotation polarization measurements of 134 pulsars these authors concluded that the Galaxy has a global field of bisymmetric spiral configuration. The magnetic field goes along the spiral arms, being strong in the interarm region and reversing direction within the arms. Han and Qiao (1994) stressed that an arm determined by magnetic field reversal is in good coincidense with the location of the long Car–Sgr arm outlined by Grabelsky *et al.* (1988) with the giant molecular clouds. It coincides therefore with this arm delineated by superclouds.

Recently Vallée (1995) has done a statistical analysis of the pitch angle values derived from data on magnetic fields, dust, gas and OB stars. He concluded that the most probable pitch angle value is 11°-14° and together with the observed 2.6–3 kpc arm separation (Sgr–Per) this implies a four-arm spiral pattern. He insisted also (Vallée, 1996) that the Galaxy has an axisymmetric magnetic field and its reversals occur within interarm regions, contrary to what was supposed by Han and Qiao (1994).

6.2 The Second Arm

Having in the mind that the probable arm class of the Galaxy is 9 or even 12 (implying a symmetric two-arm pattern), we tried to outline the probable location of the second arm, symmetric to the Car–Sgr arm (i.e. coinciding with it after turning by 180° around the centre) and with the same pitch angle of 10° as was obtained by Grabelsky *et al.* (1988) for the Car–Sgr arm. The possible grand design with these arms, designated as 1 and 2, is compared in Figure 3 with the locations of the GMCs (taken from Bronfman, 1992) and the brighter H II regions (taken from Georgelin and Georgelin, 1976) over all the Galaxy, and also with the locations of our superclouds in the Car–Sgr arm designated as arm 1 in Figure 3). The same distance between the Sun and the Galactic centre was the only assumption used to construct this composite map of the spiral arm tracers in the Galaxy.

It is seen in this picture that the arms may well start near the ends of the bar suggested by the IR-data, or from the ring around the bar (Hammersley *et al.*, 1994) as is often the case for a regular spiral structure. At any rate, the hypothetical arm 2 is delineated quite poorly and meets the string of GMCs along it only far away from the Galactic centre, in the II quadrant. It is quite significant that here behind the Per arm there are signs of a more distant optical arm (Kimeswenger and Weinberger, 1989) and we see that this arm coincides with this far segment of the second arm. Existing data on GMCs for the inner Galaxy do not outline this arm. However, as seen in Figure 2, it might start just from the near end of the bar at longitude 27°, where a region of active star formation is noted by Hammersley *et al.* (1994).

Anyway, it is worth noting that the peak at $l = 312°$ in the CO emission (Grabelsky *et al.*, 1987; Bronfman *et al.*, 1989) is close to the tangential direction to this second arm. Recall also that arm 2 is outlined also by the model of Han and Qiao (1994), as well as arm 1.

At any rate this second arm, if it exists, is much less regular than the Car–Sgr arm. Such a situation is not rare. The Southern arm in M33 is noticeably stronger and more regular than the Northern one and only the first arm has signs of a density wave. Moreover, it is a common situation: of 22 galaxies with regular strings of (supergiant) H II regions in EE83, only seven galaxies have such strings in both arms. The reason for this common asymmetry should be investigated.

6.3 Peculiarities of the Overall Distribution of GMCs

Bronfman's (1992) data for the distribution of GMCs seems to be the most useful to outline the Galaxy's grand design, being obtained with the same tools and methods over both Northern and Southern hemispheres. However, they expose some peculiarities, as seen in Figure 3.

The bulk of the GCMs within longitudes 330°–350° and, to lesser extent 15°–30°, forms two rather amorphous structures, elongated along the lines of sight, and behind them the suggested segments of spiral arms are mostly empty of GCMs. This permits the assumption that for an essential number of GCMs which fall within these features, the distances might be incorrect. Perhaps for some of them the far distances should be preferred. Note also that the longitude range 330°–30° includes just the Galactic bar according to Hammersley *et al.* (1994) and the existence of dark lanes along the sides of the bar was recently suggested by Calbet *et al.* (1996). Some of the GCMs in question may well be the constituents of these lanes and the assumed distances of the respective clouds might be wrong owing to the peculiar kinematics of the bar.

Perhaps there are also far GMCs in the longitude range 350°–15°, missed in the bright foreground of the Galactic centre. At any rate, the apparent absence of distant GMCs between longitudes 330° and 30° places the Galactic centre too far away from the centre of the overall distribution of GMCs.

6.4 Two More Arms?

Note that some chains (including one coinciding with the optical Per arm) of the spiral-arm tracers (superclouds, GMCs and giant H II regions) do not fall on the Car–Sgr arm or on its symmetrical counterpart arm 2 (Figure 3). Some of these strings might be long inner spurs from these two arms, yet such inner spurs are rather unusual in other galaxies. However, a highly symmetrical four-arm pattern exists, with the same 10° pitch angle and a 90° phase difference between the arms, which represents all the tracers but their amorphous conglomerations in the inner Galaxy, as discussed in Section 6.3.

The additional arms 1A and 2A (Figure 3) are thus exactly midway between the main arms 1 and 2. Within them there are two chains of a few superclouds and H II regions close to the Solar ring, one within longitudes 40°–60°, and another, more prominent, within longitudes 310°–325°. These chains resemble to some degree the pairs of symmetrical spurs that are observed in some galaxies and are considered to be evidence of an inner 4:1 resonance (Elmegreen, Elmegreen and Montenegro (1992). If so, this resonance is close to the Solar distance in our Galaxy.

The well-known Per arm in the Solar neighbourhood is just part of one of these additional arms, designated as 2A. Inside the Solar ring this arm is delineated very uncertainly, and arm 1A even more so, ending with the chain of tracers at longitude 325°, as discussed above. Another possibility, suggested by Figure 3, is that the optical Per arm seen near the Sun is the inner long spur of the second main arm 2. It is worth noting also the difficulty of seeing the Ori–Gyg arm in Figure 3, one more piece of evidence that it is the Local spur.

This hypothetical symmetric four-arm design might correspond to the real situation only if it admits the absence of any spiral-arm tracers along long parts of three of these arms, including the second of the main arms, that of Sct–Cen. A similar situation is often the case in other galaxies (yet recall the possibility described in Section 6.3 above).

The supergiant CO complex at longitude 332° and adjacent ones are regarded by Bronfman *et al.* (1989) as belonging to the Nor arm, which is internal with respect to the Sct–Cen arm. Yet they may correspond to the very start of the Car–Sgr arm and to the region of star formation at the far end of the bar (Calbet *et al.*, 1996), as shown in Figure 3 following the model of Hammersley *et al.* (1994, Figure 9). It follows from their data that the peaks of 12-micron and CO emission, connected with dust matter and located at both sides of the Galactic centre, are at the inner sides of stellar arms, indicated by 2-micron peaks. This is what is expected for grand design spirals inside the corotation radius.

7 SUMMARY

Our main conclusions may be summarized as follows. The locations of H I/CO superclouds along arm 1, Car–Sgr, indicate that the Milky Way system belongs to the class of galaxies with regular strings of giant gas–star complexes along the arms. Such arms should be connected with spiral density waves. There is increasing evidence that these waves are often strong enough to enhance the density of the old disc stars as well as older star clusters. The observational data for the stars and clusters in the local segment of the Car–Sgr arm demonstrate that this is the case for this arm. The implied two-fold arm–interarm density contrast is high, yet is observed in a number of galaxies. The long lifetime of such strong spiral density waves implies that they are driven either by the bar or by a component galaxy, or the supply of infalling gas clouds (e.g. Gonzales and Graham, 1996). The Galaxy surely has all these three properties.

The spacing of superclouds along arm 1 displays a bimodal distribution, the distances of about $0.1R_0$ and $0.2R_0$ being highly preferred. It looks as if the fundamental spacing is $0.1R_0$, yet at some positions gas–star complexes are absent or too faint to be observable. There is some indication that the spacing is larger in the outer Galaxy. Similar situations are observed in a number of other galaxies.

Most of the galaxies with long and regular chains of gas–star complaxes along the arms belong to Elmegreens's arm class 9 or 12, implying the presence of two symmetric arms. However, arm 2, Sct–Cen, symmetrical to the Car–Sgr arm, is poorly outlined, being most noticeable only in the II quadrant as the far arm behind the Per arm. This is also usually the case for other galaxies, the regular spacing of superclouds having been observed mainly along only one arm. These arms 1 and 2, together with two other symmetrical fainter arms located just between them, would fit the positions of GMCs and giant H II regions all over the Galaxy. The common Per arm is just one of these additional arms, otherwise it would be an inner spur from arm 2, which is unlikely.

The four-arm symmetrical pattern for the Galaxy implies the existence of long non-populated segments of arms and this is also not unusual in other galaxies. The distribution of spiral tracers in the Galactic plan is compatible with the four-arm grand design yet does not prove its existence. Anyway, as Vallée (1995) pointed out, the pitch angle of about 12° and the very plausible assumption that the Local arm is nothing but a spur is compatible only with the four-arm structure. The local value of the pitch angle for the Car–Sgr arm is 20°, and this large value is explained by the local meandering of the arm (Alfaro *et al.*, 1992). It is possible also that the concentration of light-absorbing clouds near the Sun in I quadrant (including the Agl, Vul and Cyg rifts) is responsible for this (then apparent) meandring (Efremov, 1997).

At any rate, the data on superclouds used here prove only the existence of the very long regular Car–Sgr arm, other suggestions on the Galactic grand design being only tentative. Note that the Car arm in the IV quadrant is well represented also in Figure 15 of McGee and Milton (1964), who found six superclouds, yet their other arms are farther away from the centre of the Galaxy than those outlined in Figure 3. Anyway, it is not surprising that the outer superclouds have no molecular counterparts, the fraction of molecular to atomic hydrogen being lower at the outskirts of the Galaxy.

The distance of superclouds used here are mostly kinematical and are connected with the old values of the Galactic centre distance and the rotational curve. They are, however, the same as those used in determinations of the distances of GMCs in the previous work, including those plotted in Bronfman's (1992) map, which is the basis of our Figure 3. As is seen in this figure, the largest of these GMCs do indeed coincide with the H I superclouds and the self-consistency in distances was retained. The maps of H I superclouds, giant H I regions and GMCs were adjusted to each other in Figure 3, the only assumption being that the distance between the Sun and the centre is the same, no matter what the actual distance is. Note also that the Car–Sgr arm outlined by H I superclouds and GMCs coincides quite well with the longest H I arm of the old Weaver (1970) picture (Figure 1), its pitch angle being 12°.

The relative pattern of spiral arms would probably be only slightly affected by the new distances. Anyway, the better distances, with account taken for the existence of the bar (e.g. Wada *et al.*, 1994) surely should be involved in future considerations, as well as the data for superclouds over the Galaxy. Recall that those used here are restricted to the I quadrant and to the strip along the Car arm in the IV quadrant. They give the hope, however, that the data for superclouds over all the Galaxy would give the best way to study its grand design.

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