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ON THE GALACTIC SPIRAL PATTERNS: STELLAR AND GASEOUS

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ABSTRACT

The gas response to a proposed spiral stellar pattern for our Galaxy is presented here as calculated via 2D hydrodynamic calculations utilizing the ZEUS code in the disk plane. The locus is that found by Drimmel (2000) from emission profiles in the K band and at 240 μm. The self-consistency of the stellar spiral pattern was studied in previous work (see Martos et al. 2004). It is a sensitive function of the pattern rotation speed, Ω_p, among other parameters which include the mass in the spiral and its pitch angle. Here we further discuss the complex gaseous response found there for plausible values of Ω_p in our Galaxy, and argue that its value must be close to 20 $km\ s^{-1}\ kpc^{-1}$ from the strong self-consistency criterion and other recent, independent studies which depend on such parameter. However, other values of Ω_p that have been used in the literature are explored to study the gas response to the stellar (K band) 2-armed pattern. For our best fit values, the gaseous response to the 2-armed pattern displayed in the K band is a four-armed pattern with complex features in the interarm regions. This response resembles the optical arms observed in the Milky Way and other galaxies with the smooth underlying two-armed pattern of the old stellar disk populations in our interpretation. The complex gaseous response appears to be related to resonances in stellar orbits. Among them, the 4:1 resonance is paramount for the axisymmetric Galactic model employed, and the set of parameters explored. In the regime seemingly proper to our Galaxy, the spiral forcing appears to be marginally strong in the sense that the 4:1 resonance terminates the stellar pattern, despite its relatively low amplitude. In current work underway, the response for low values of Ω_p tends to remove most of the rich structure found for the optimal self-consistent model and the gaseous pattern is ring-like. For higher values than the optimal, more features and a multi-arm structure appears.

Key words : Galaxy: kinematics and dynamics – Galaxy: spiral – Galaxy: fundamental parameters – Galaxy: structure – ISM: structure

I. INTRODUCTION

In a recent paper (Martos et. al 2004, hereafer P1), a best fit model constrained by self-consistency was presented for the stellar spiral pattern of our Galaxy. For the Galactic parameters explored in that work and previous studies (Pichardo, 2003; Pichardo et. al. 2003; Pichardo, Martos and Moreno 2004), the best fit was found for a value of the pattern speed of $\Omega_p = 20\ km\ s^{-1}\ kpc^{-1}$. The imposed spiral locus was the 2-armed pattern found by Drimmel (2000). Calculating the gas response to such pattern, we obtained a 4-armed pattern with multiple interarm features which we identified with the optical pattern observed in our Galaxy. This interpretation is consistent with a prediction laid down by Drimmel and Spergel (2001).

The value of the pattern speed of the Galaxy has been a matter of controversy for a long time. From the values proposed by Lin, Yuan & Shu (1969) of $\Omega_p = 11 - 13\ km\ s^{-1}\ kpc^{-1}$, numbers in the range of 10-60 $km\ s^{-1}\ kpc^{-1}$ have appeared in the literature (see, for instance, Andrievsky et. al. 2003).

The conventional picture of the spiral pattern of the Milky Way maps at least 4 arms, named Norma, Crux-Scutum, Carina-Sagittarius, Perseus (for a recent review see Vallée 2002, who also reports a likely pitch angle of 12 degress for this pattern). Additionaly, features such as the Orion spur at the Solar neighborhood, have been revealed (Gorgelin & Gorgelin 1976). Recent data shed light into this picture, providing a deeper understanding of the Galactic spiral structure. Drimmel (2000) presented emission profiles of the Galactic plane in the K band and at 240 μm. The former data set, which suffers little absorption and traces density variation in the old stellar population, is dominated by a two-armed structure with a minimum pitch angle of 15.5 °. At 240 μm, the pattern is consistent with the standard four-armed model, that corresponding to the distribution of the youngest stellar populations delineated by HII regions.

A continued line of work by Contopolous and collaborators (see, v.g. Patsis, Grosbøl and Hiotelis 1997 and references therein) has provided a framework to study the response of gaseous disks to spiral perturbations. In that paper, a comparison between SPH models with Population I features observed on B images of normal, grand design galaxies, showed that the 4:1 reso-

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nance generates a bifurcation of the arms and interarm features. Furthermore, Contopoulos & Grosbøl (1986, 1988) had shown that the central family of periodic orbits do not support a spiral pattern beyond the position of the 4:1 resonance, which thus determines the extent of the pattern. Weak spirals can extend their pattern up to corotation from linear theory. A phenomenological link betweeen resonances, the angular speed, and the stellar and gas patterns in spirals is complemented by the study of Grosbøl & Patsis (2001): using deep K band surface photometry to analize spiral structure in 12 galaxies, the two-armed pattern radial extent was found consistent with the location of the major resonances: the inner Lindblad resonance (ILR), the 4:1 resonance, corotation and the outer Lindblad resonance (OLR). For galaxies with a bar perturbation, the extent of the main spiral was better fitted assuming is limited by Corotation and the OLR.

II. OUR MODEL

In P1, our axisymmetric Galactic model is that of Allen & Santillán (1991), which assembles a bulge and a flattened disk proposed by Miyamoto and Nagai (1975), with a massive spherical dark halo. The model is suitable for this particular work for its mathematical simplicity, with closed expressions for the gravitational potential. The main parameters are: $R_{sun} = 8.5$ kpc as the Sun's galactocentric distance; an observationally constrained rotation curve which flattens at a moderate speed of about 200 $km\ s^{-1}$ from a peak value of 220 $km\ s^{-1}$, and a total mass of $9 \times 10^{11} M_{sun}$ within 100 kpc. We added to this mass distribution a spiral pattern modeled as a superposition of inhomogeneous oblate spheroids placed along different loci (for details, see Pichardo 2003; and Pichardo et al. 2003). One locus is the fit to the K band data of Drimmel (2000), a two-armed spiral with a pitch angle of 15.5°. The arms start from the tips, at a R of 3.3 kpc, and at right angles, of a line segment passing through the Galactic center. The orientation is such that the line segment makes an angle of 20° with the Sun-Galactic center radius, and is aligned with the assumed Galactic bar orientation (Freudenreich 1998; Pichardo, Martos and Moreno 2004). The minor axis of the spheroids is perpendicular to the Galactic plane, extending up to 0.5 kpc; the major semiaxes have a length of 1 kpc. Each spheroid has a similar mass distribution, and the central density falls along the arm locus up to a Galactic distance of truncation of 12 kpc. The total mass in the spiral is such that provides local ratios of spiral to background (disk) forces of certain magnitude. Seeking reasonable values of that ratio, we used the empirical result of Patsis, Contopoulos and Grosbøl (1991); in this work, self-consistent models for 12 normal spiral galaxies are presented, with a sample including Sa, Sb and Sc galaxies. Their Figure 15 shows a correlation between the pitch angle of the spiral arms and the relative radial force perturbation. The forcing, proportional to the pitch angle, is increasing from Sa to Sc types in a linear fashion. For our pitch angle of 15.5°, the required ratio for self-consistency is between 5% and 10%; the ratio is a function of R. The authors consider strong spirals those in which the ratio is 6% or more. A strong spiral is expected to terminate its pattern at the location of the 4:1 resonance for self-consistency.

We found that, in order to obtain relative force perturbations in the 5% to 10% range, our model requires a mass in the spiral pattern of 0.0175 M_D, where M_D is the mass of the disk. With that choice, our model predicts a peak relative force of 6%, and an average value, over R, of 3%. Other masses were explored, but the analysis favours this case (see below), borderline but on the weak side of the limit separating linear (weak) and non-linear (strong) regimes considered by Contopoulos & Grosbøl (1986, 1988). It is worth noticing that the latter results were obtained in galactic models quite simplified in comparison with the one employed here. Also, the relative amplitude of the spiral perturbation has been taken as a fixed number, a few percent of the axisymmetric force in all work we know of for our Galaxy; for instance, Yuan (1969) proposed 5%.

III. SELF-CONSISTENCY

Following Contopoulos & Grosbøl (1986), in Pichardo et al. (2003) the stellar density response to the proposed spiral density distribution was calculated assuming that trapped orbits around an unperturbated circular orbit and with the sense of rotation of the perturber are also trapped around the corresponding central periodic orbit in the presence of the perturbation. Thus, a series of central periodic orbits are computed and the density response is calculated along their extension, using mass flux conservation between two succesive orbits. Then the position of the density response maxima along each periodic orbit, and the positions of the response maxima in the Galactic midplane, are found. These locations are compared with the spiral locus, and the average density response around each maximum is calculated taking a circular radius about it of the same semiaxis of the spheroids in the model. The ratio of the average density response and the imposed density is the merit function for the self-consistency criterion we consider the model must satisfy.

For the spiral mass satisfying our expected spiral amplitude, the ratio of densities obtained for $\Omega_p = 20\ km\ s^{-1}\ kpc^{-1}$ provides an excellent test of self-consistency. It is an almost flat function of R (Pichardo 2003), with values between 1 and 1.2 in the radial (R) interval [3.8,7.3] kpc. Large departures from this flat response were found for other values of Ω_p close to the prefered solution. These values were explored within a wider range of R, [3.3, 10.3] kpc. Other parameters (spiral mass and pitch angle, two-armed pattern) are fixed. The values were: 19, 21, 22.5, 25 $km\ s^{-1}\ kpc^{-1}$. In Figure 1, we show the results for the case $\Omega_p = 19\ km\ s^{-1}\ kpc^{-1}$. On the Galactic plane, the as-

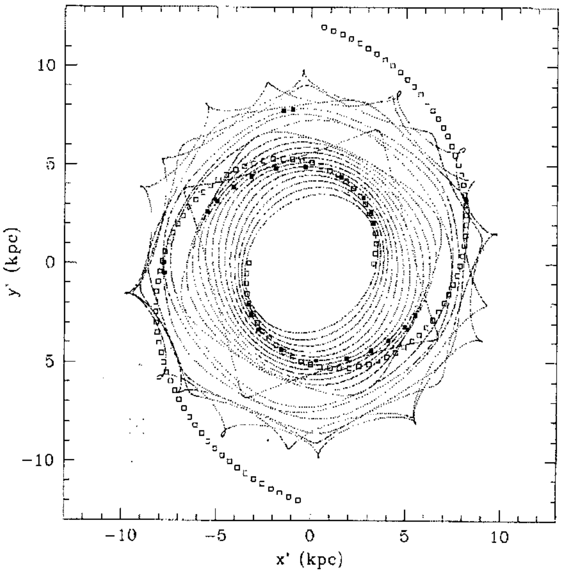

Fig. 1.— The self-consistency analysis for $\Omega_p = 19$ $km\ s^{-1}\ kpc^{-1}$. The proposed spiral locus is shown with open squares. A set of periodic orbits are traced with continuous lines, and the maxima in density response are the filled (black) squares. The frame of reference is the rotating one where the spiral pattern is at rest, with origin at the Galactic center.

sumed spiral pattern and a set of stellar periodic orbits are drawn. The density maxima locations, described above, are also pictured. The boxy-like orbit is the 4:1 resonance. In the old kinematical-wave interpretation of orbital support for the spiral, one can see support inside the resonance, and an abrupt change corresponding to an off-phase response to the spiral outside it. This figure may be directly compared with Figure 1 of P1. While there are large discrepancies in the stellar response, as the merit function for this value of Ω_p departs very much from the optimal response for $\Omega_p = 20$ $km\ s^{-1}\ kpc^{-1}$ (displayed in P1), the gas response is quite similar for both values. In other words, self-consistency is a rather delicate test with a precise value that maximizes the merit function. On the other hand, the hydrodynamic gas response as shown in Figure 2 is much more robust, varying only in a slow fashion with Ω_p. This also applies to the behavior here displayed that the pattern would be dynamically terminated at the position of the 4:1 resonance, as predicted by Contopulos and colaborators. Drimmel and Spergel (2001) find that the arm strength begins to fall off inside the Solar circle at about .85 R_{sun}, which, for our Galactic model-assumed $R_{sun} = 8.5$ kpc, corresponds to 7.2 kpc.

IV. THE GAS RESPONSE

Our Figure 2 shows the gas response to the imposed pattern, whose locus is indicated with open squares. The numerical grid is cylindrical, and covers 2 Π radians and a radial range of 3.3 to 15 kpc. The zone inside that inner boundary is physically meaningless, reflecting only the initial conditions of the simulation. Calculations were performed utilizing the 2D, hydrodynamic version of ZEUS (for a description of the code, see Stone & Norman, 1992a, b). There are 500 X 500 zones in the (Eulerian) grid, and the snapshot corresponds to a time of evolution of 1.6 Gyr. The system is initialized with outflow radial boundary conditions, and velocities from the Galactic model rotation curve, adding the spiral source terms through a input table for ZEUS. The disk reaches a nearly steady state rapidly as shown in this figure, which was followed up to 3 Gyr. The arrows are velocities in the rotating frame; the maximum size represents 212 $km\ s^{-1}$. The initial gas density is exponential, with a radial scaleheight of 15 kpc and the local value of about 1 cm^{-3}. The temperature was fixed at 8000 K, and the simulation is isothermal given the short cooling timescales compared to the dynamical timescales. The pattern is rotating at 19 $km\ s^{-1}\ kpc^{-1}$. In grey scales, the density gas response shows 4 arms and additional features. The shock strength along a "gaseous" arm varies along its extension.

In work currently underway, we have found (Yáñez and Martos 2004) that for low Ω_p (of the order 10 $km\ s^{-1}\ kpc^{-1}$), much of the rich structure is removed, rendering a ring-like pattern. High values (of the order of 40 $km\ s^{-1}\ kpc^{-1}$) tend to produce a more complex gas pattern. This is seemingly revealing the strong link between resonances in the stellar orbits and the gas structure. We notice that the strength of the shocks will considerably diminish in a full 3D, MHD simulation (the inclusion of the vertical direction and magnetic field was considered in Martos & Cox 1998). Secondly, the response is just too sensitive to the details of the potential to be conclusive. Recent simulations in realistic Galactic models are scarse: Gómez-Reyes & Cox (2002) employed the Galactic model of Dehnen and Binney (1998). However, their value of Ω_p (12 $km\ s^{-1}\ kpc^{-1}$) places the 4:1 resonance beyond 22 kpc, far out from the observed pattern extent. Another important component not included yet in these simulations is the Galactic bar, which we recently modeled in three ways (Pichardo, Martos & Moreno 2004). As discussed in P1, we do not expect a strong effect at the Solar circle, but the bar will affect the dynamics not too far away from that position towards the inner Galaxy. A plausible assumption is that R = 3.3 kpc corresponds to the bar corotation. If the study of Grosbøl & Patsis (2001) applies, one would say that the termination of the "main" spiral pattern with a bar probably corresponds to the position of corotation or the OLR. In the following, we discuss independent studies that are consistent with the picture here described.

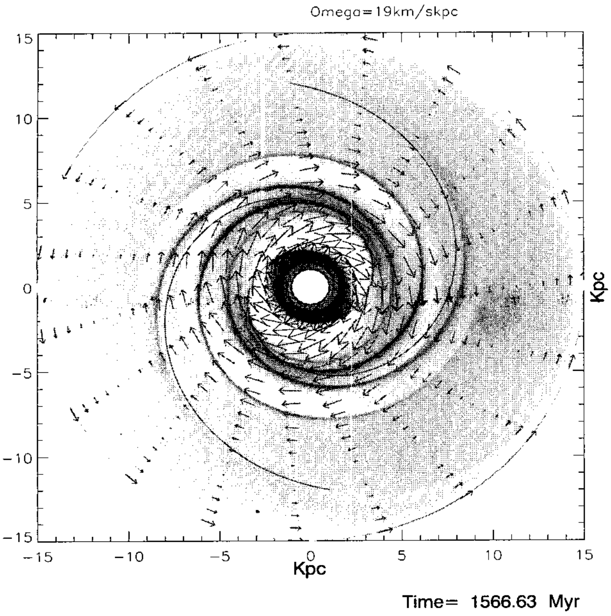

Fig. 2.— A simulation with the code ZEUS of the gas response to a spiral pattern with $\Omega_p = 19$ $km\ s^{-1}\ kpc^{-1}$ in the rotating frame of the spiral pattern (the primed x-y plane of Figure 1). The arrows give the velocity field, and their size is proportional to the speed. The maximum size in the grid corresponds to 212 $km\ s^{-1}$. The elapsed time is 1.6 Gyr. In grey scales, dense zones correspond to dark regions. This simulation is isothermal with 500 X 500 zones in cylindrical coordinates. The imposed spiral pattern is illustrated with the solid line.

V. STAR FORMATION IN THE GALAXY

For values of $\Omega_p = 20$ $km\ s^{-1}\ kpc^{-1}$ or closer, one can obtain from Figure 2 the surface density along a circle with the radius of the Sun orbit. In the most simplistic approximation (the orbit has radial excursions of the order of 2 kpc), there are two main peaks of similar densities, and several local maxima. The mass contrast is consistent with K-band observations (Kranz, Slyz & Rix 2001), who quote an arm/interarm density contrast for the old stellar population of 1.8 to 3 for a sample of spiral galaxies. Interestingly, these two peaks have surface densities in agreement with the expected threshold density for star formation, with a value of approximately 10 M⊙ pc^{-2} (Kennicutt 1989), in which we are considering the reduction in the shock compression due to the magnetic field and the 3D dynamical effects. Other local maxima are factors of 3 or more lesser than that value, making any burst of star formation a less likely event. Now, with a $\Omega_p = 20$ $km\ s^{-1}\ kpc^{-1}$, the time baseline for a circular orbit of that radius is very approximately 1 Gyr, with our assumed Solar galactocentric distance. We found then two similarly spaced episodes of vigorous star formation over the last Gyr. To test this prediction, we compare with a recent star formation history of the Hipparcos Solar neighbourhood, by Hernández, Valls-Gabaud and Gilmore (2000). Using Bayesian analyisis techniques to derive the star formation history over the last 3 Gyr, they find an oscillatory component of period of nearly 0.5 Gyr, in remarkable agreement with our result, over a small level of constant star formation. In consistency with these two independent determinations, de la Fuente Marcos and de la Fuente Marcos (2004) obtain, by studying the age distribution of young globular clusters, a periodicity in the recent star formation history at the Solar circle of 0.4 ±0.1 Gyr.

VI. COSMIC RAY DIFFUSION FROM SPIRAL ARMS

Shaviv (2002) finds that the CR flux reaching our Solar System should periodically increase with each crossing of a Galactic spiral arm. Along the same lines of last section, over a time baseline of the past 1 Gyr, we added our estimated magnetic field compression form Martos & Cox (1998) to plot the expected synchrotron flux variations moving along the Solar circle and assuming the mass distribution fixed in time. There are 6 local maxima in our plot with fluxes that are higher than today's flux. This is the same number of peaks satisfying that condition in Shaviv's work, who plots the ratio cosmic ray flux/today's cosmic ray flux obtained from a sample of 42 meteorites, which is related there to climate changes in Earth. Shaviv (2002) reports a period of 143 Myr for the episodes (crossings) from meteorites data. In our framework, crossings occur on the average every 167 Myr, not equally spaced in time. Interestingly, there is a delay of about 25 Myr to be expected in synchrotron emission because of the time after the ionizing photons are emitted, plus the time for cosmic ray diffusion, as discussed in Shaviv (2002). Shaviv assumes 4 arms and a termination of the pattern at the 4:1 resonance. This is the behavior we found for the stellar self-consistency, but from the fact that the K band and the optical pattern are observed to extend further out, it is likely that the analysis must be revised.

VII. CONCLUSIONS

To clarify matters, a higher difference in speeds between the pattern and the local speed of the large scale flow of gas, which increases from corotation inwards, does not necessarily imply a stronger shock. What is critical (see Martos & Cox 1998) is the comparison between the kinetic energy of the gas flow and the potential well the spiral arm represents at some locations. We stress the point that, with the addition of the spiral pattern modeled as a structure from a mass distribution, vs the usual perturbing term commonly used in the literature, the resulting gravitational potential becomes a strong function of the position in the disk, even with the smooth, continuous distribution we propose.

Reality must be more complex. As a consequence, an arm does not always represent a potential well, and along a given spiral arm, the compression from the gas flow encounters will be a sensitive function of the coordinate along the locus, specially at R in the range of 4 or more kpc. This is reflected in Figure 2.

With uncertainties in structural parameters in our Galaxy, one can hardly expect exact agreement between models. Our very limited modeling effort points to a particular value of Ω_p, 20 $km\ s^{-1}\ kpc^{-1}$ that maximizes the self-consistency criterion we utilized. As found by Contopoulos & Grosbøl (1988), that self-consistency analysis is improved introducing dispersion of velocities; this is a realistic effect that can be neglected arguing that in strong spirals nonlinearity dominates. For our Galaxy, we did not explore the region betweeen the 4:1 resonance and corotation in enough detail to claim that our Galaxy is a strong spiral. It appears rather weak from the observed patterns. However, the response at the best Ω_p is so flat that does not seem to need the aid of a dispersion of velocities. Other values of Ω_p could be improved by this effect and give as good a response. In particular, from our results, values close to 20 $km\ s^{-1}\ kpc^{-1}$ appear as reasonable candidates, as that of Figure 1. Much more work remains to be done. The inclusion of the bar should provide further insight into the structural details, but the reported, large differences between the angular speeds of bar and spiral complicate the dynamical coupling (Bissantz, Englemaier & Gerhard 2003 find a best model coupling at speeds of 60 $km\ s^{-1}\ kpc^{-1}$ for the bar and 20 $km\ s^{-1}\ kpc^{-1}$ for the spiral, using SPH models).

The detailed gaseous response for different values of Ω_p, in the presence of large scale magnetic fields is work currently underway and will be presented elsewhere (Yáñez and Martos 2004). The link betweeen resonances in the stellar orbits and the complex gas response is also worth exploring further, as the study of Chakrabarti, Laughlin and Shu (2003) indicates.

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