CORRUGATIONS

Spatial and Kinetic Structures

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Abstract Gas and stars in the Milky Way show quasi-periodic vertical deviations from the formal galactic plane. This kind of pattern, so named corrugation, seems to be a general phenomenon affecting the disk galaxies. Recent studies, both theoretical and observational, have shown that similar structures might appear in the field of the velocity vertical component and could be derived from the radial velocity maps of face-on galaxies. The mechanisms which generate these spatial patterns are connected with those able to arrange the gas and form the large fertile clouds where stars will born. Different proposed models for the generation of corrugations anticipate distinct velocity fields providing a good observational test to these mechanisms.

1. Introduction

While studying the galactic distribution of HI in order to define a more precise galactic coordinate system, Kerr (1957) and Gum et al. (1960) noted that the HI centroids distributed above and below the equatorial plane in a sinus-wave like structure. They named this structure "corrugation". Later studies on gas and young star distribution along the galactic spiral arms (e.g. Dixon 1967; Spicker & Feitzinger 1986; Alfaro et al. 1991; Malhotra 1995) corroborated that assertion and showed that the galactic plane is far from planarity.

The same tracers used to devise the three-dimension spatial pattern of the galactic plane form the observational basis for studying the star-forming processes and have been utilized to determine the places and scales of the star-forming regions in this and other galaxies (e.g. Efremov 1978; Elmegreen & Elmegreen 1983; Avedisova 1989; Alfaro et al. 1992a, b). Star formation in spiral galaxies often appears to occur in large gas complexes or spiral arm segments with characteristic sizes of the order of 1 kpc and masses of the order of 10^7 solar masses, typically containing one or more giant HII regions and in some cases massive young clusters (Larson 1988). To investigate the typical mass of the clouds, length scale, spacing between clouds and amplitude of the vertical displacements, as function of properties of the host galaxy scaled by the galactocentric radius, appeared as a necessary task to better know the physical mechanisms generating the corrugations.

Studies on the amplitudes and scales of the spatial corrugations are mainly restricted to our Galaxy where we can obtain a three-dimension picture for the gas and stellar components, due to our singular position inside the galactic disk. The arrangement of giant HII regions along spiral arms have been analyzed for a large sample of face-on galaxies (e.g. Elmegreen & Elmegreen 1983) but its connection with the vertical structure can not be established as in the Milky Way. Corrugated patterns in other galaxies have been only reported for three or four cases (Arp 1964; Florido et al. 1991) and are limited to edge-on objects where, in addition, the observed structure is the product of the superposition of several components at different galactocentric radius. Thus, data on spatial corrugations alone are shown to be very limited to discriminate among the different models envisaged to arrange and organize the interstellar matter into fertile gas clouds. Is, therefore, this way close? Recent theoretical works have generated corrugation models which predict not only the spatial distribution of the gas clouds but the associated velocity field too. Otherwise, some observational papers start to deal with the characterization of the vertical component of the velocity; a term forgotten in most of the works on kinematics of disk galaxies. Perhaps the answer is running in the field.

Here we present a brief review of the main observational works of these structures (section 1), discuss in more detail two specific generation mechanisms; hydraulic jump and 3D Parker instability (section 2), and, finally, point out the main guidelines for an observational project aimed to characterize the kinetic properties of the corrugations in disk galaxies (section 3).

2. Observational summary

Corrugations have been observed in different spectral ranges. Afterward their detection, corrugations were observed for different stellar and interstellar tracers: HI (Quiroga 1974; Lockman 1977; Spicker & Feitzinger 1986; Malhotra 1995); CO molecular clouds (Lockman 1977; Malhotra 1995); HII regions in radio and visible wavelengths (Lockman 1977; Spicker & Feitzinger 1986); SN remnants (Lockman 1977); OB stars (Quiroga 1974; Kolesnik & Vedenicheva 1979; Spicker & Feitzinger

1986; Cepheid stars (Berdnikov & Efremov 1993), Wolf-Rayet stars (Alfaro et al. 1992a); young clusters with log(age) $\leq 10^7$ yr (Alfaro et al. 1991, 1992b); U surface brighness (Schmidt-Kaler & Schlosser 1973); Hα, R and I bands in radial profiles of external galaxies (Florido et al. 1991) and corrugated magnetic field lines has been observed in the southwest arm of M31 (Beck et al. 1989).

The corrugations appear along azimuthal and radial lines. Periodical vertical displacements have been detected throughout different spiral arms in our Galaxy (Dixon 1967; Quiroga 1974; Spicker & Feitzinger 1986; Alfaro et al. 1992b; Berdnikov & Efremov 1993). Clear systematic deviations are also detected along different circles centered at the Sun (Kolesnik & Vedenicheva 1983; Alfaro et al. 1992a). Radial distributions have been reported for constant azimuth lines (Lockman 1997), for different values of the galactocentric radius (tangential point; Malhotra 1995), and radial profiles in edge-on galaxies (Florido et al. 1991).

Typical length scales and amplitudes have been derived for different tracers in the Milky Way. The most complete study refers to HI distribution along different spiral arms (Spicker & Feitzinger 1996). They report azimuthal wavelengths in three different ranges: (a) 1 kpc $\leq \lambda \leq$ 2 kpc; (b) 4 kpc $\leq \lambda \leq$ 8 kpc; (c) 13 kpc $\leq \lambda$ and amplitudes between 40 and 350 pc. A spatial wavelength of 2.4 kpc with an amplitude of 40 pc were estimated for the young open clusters along the Carina-Sagittarius arm (Alfaro et al. 1992b), while Dixon (1967) derived a value of 1.2 kpc from the OB star distribution.

Several mechanisms have been postulated for generating these structures (Alfaro & Efremov 1996): gravitational and magnetic instabilities (e.g. Nelson 1985; Kim et al. 1997); interaction between a self gravitating disk in a axis-symmetric halo (Sparke 1995); interaction between galaxies (Edelsohm & Elmegreen 1997); high velocity cloud collision with the galactic disk (Franco et al. 1995); and gas-arm encounters (Roberts 1969). All these models also predict z-velocity corrugated patterns associated to the spatial structure, however, the expected amplitude was, in most cases, lesser than 10 kms^{-1}. Therefore, when observations of face-on galaxies showed extended velocity components with dispersions of the order of 20 kms^{-1}, they were attributed to other phenomena and the vertical component of the velocity was forgotten in the kinetic analysis of galactic disks (Alfaro et al. 2001; Gómez & Cox 2002). Nevertheless, our conception of the galactic ISM has suffered drastic changes in the last decade. Now the interstellar medium is thicker, and has a higher pressure than previously thought (Boulares & Cox 1990; Martos & Cox 1998). What should be the answer of this medium to the different perturbations listed above? Such a medium would be more likely to display vertical motions with detectable amplitudes. We discuss this point in more detail below.

3. A magnetized thick disk

The gaseous disk of spiral galaxies is a magnetized fluid with several gas components and a very complex structure (e.g. Martos & Cox 1998; Cox 2000). The atomic and molecular clouds are embedded in a more diffuse and ionized medium that extends several hundred parsecs, even kiloparsecs, above the midplane. The magnetic field is attached to the host galaxy via ionization of the neutral gas clouds which behave as actual anchors (see Franco et al. 2002a for more details). It is almost certain than nonthermal pressure component drops off less rapidly than the density, requiring magnetic tension to hold things together (Boulares & Cox 1990). Thus, in this extended atmosphere, the answer of the system to local perturbations, driven from different triggering agents, would be radically different than the expected for a more classical (thiner) ISM structure, generating new and completely different disk/halo mass exchange mechanisms (e.g. Martos & Cox 1998; Martos et al. 1999; Santillán et al. 1999; Kim et al. 2000; Franco et al. 2002b; Gómez & Cox 2002). Two cases: Parker instabilities along spiral arms and the interaction between the gas and a passing spiral arm deal with the generation of corrugated vertical velocity fields.

When a relatively well-ordered B field is present in a gaseous disk, the compression generated by a strong perturbation changes the magnetic field downstream, and the gas driven by the distorted field lines accumulates large-mass clouds along the valleys of the field lines (Parker 1966). This happens when the wavelength of the distortion is larger than a critical value and it is known as Parker instability. The instability has two independent modes, undular and interchange, with different properties and wavelengths that combine into a mixed 3D mode, and as in the case of gravitational instabilities, it may also gather giant clouds complexes in spiral arms (e.g. Mouschovias et al. 1974; Elmegreen & Elmegreen 1986). More recently, with a three-dimensional model of the Parker instability in a thin disk and under uniform gravity, the actual possibility of forming large cloud complexes has been questioned (e.g. Kim & Hong 1998). We wonder if a thicker and magnetized disk, as the one proposed by Cox and collaborators, would show the same behaviour. For this case the instability produces a clear arm/interarm difference (Franco et al. 2002b); triggering the formation of large interstellar clouds inside the arm but generating only small structures of low density in the interarms regions. The resulting clouds are distributed in an antisymmetric

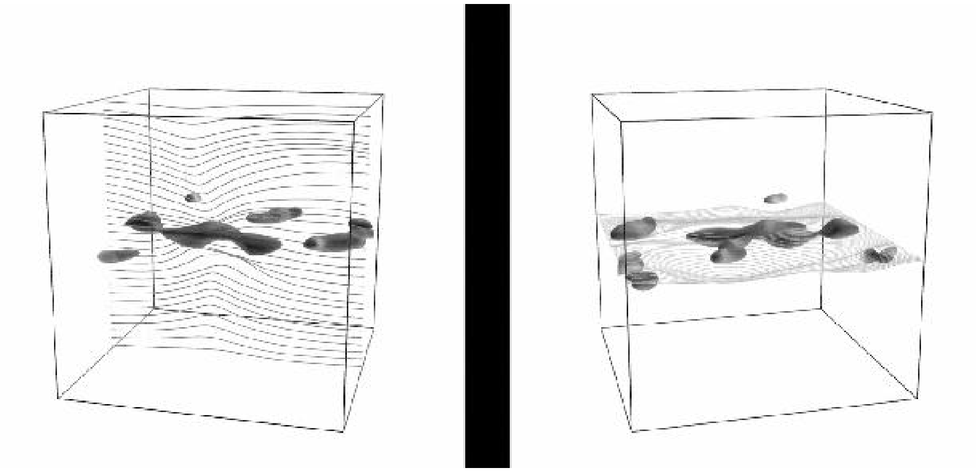

Figure 1. Magnetic field lines near the central *(left)* y-z and *(right)* x-y planes, together with isodensity surfaces with $n = 0.8$ cm^{-3}.

way with respect to the midplane, and the masses are similar to those inferred for large gas superclouds in our Galaxy (see Figure 1).

Such a cloud distribution results in an azimuthal corrugation along the arm, and for physical conditions similar to those of the optical segment of the Carina-Sagittarius arm, it has a wavelength of about 2.4 kpc in good agreement with the value derived by Alfaro et al. (1992a) for this arm. This structuring, then, can explain the origin of both gas superclouds and the azimuthal corrugations in spiral arms. Otherwise, the distribution of the z-velocity component along the arm has been also estimated where we can see an undulated field, with an amplitude of about 10 km s^{-1}. Vertical motions associated to spiral density waves had been previously advanced (Fridman & Polyachenko 1984) but the z-velocity component, for this model, is expected to show an odd symmetry with z.

Early studies on spiral density waves showed that the interaction of gas flows with density enhancements produces shocks, even for weak density perturbations (Roberts 1969). This result generated an extensive work on their possible consequences for star and molecular cloud formation. A review of the different approaches used to tackle the modelisation of this interaction has been recently published by Franco et al. (2002a). First models worked with zero thickness disks where only three parameters control the problem in this approximation: the signal speed in the medium, the relative gas/spiral arm speed and the amplitude of the perturbation. Stationary shocks (restricted to the galactic plane) only appear for critical gas entry speed v_c and when the flow speed is smaller than v_c the gas tends to pile up in the well rather than forming a shock.

The inclusion of an extended magnetized disk radically changes the answer (Martos & Cox 1998; Gómez & Cox 2002). The resulting shocks and density enhancements also occurs at high z above the spiral arm. The interaction leads to the formation of a complex network of shocks and a hydraulic jump, that sends material to high latitudes. The gas entering a spiral arm rises suddenly on the upstream side of the arm then accelerates and bends downward, finally landing on a large downfall region downstream of the arm. This scenario fits quite well the phenomenology found in NGC 5427 (Alfaro et al. 2001). The observed deprojected velocity amplitudes are of the same order as the ones found by Martos & Cox (1998) and Gómex & Cox (2002). The comparison between Figure 2 in Alfaro et al. (2001) and a synthetic Hα observation derived from a 3D hydraulic jump model (Figure 17 in Gómez & Cox 2002) displays many similitudes and a few differences. The principal difference lays on the relative position between the velocity and emission peaks which could be accounted for the imprint of radial streaming motions in the plane of the galaxy owing to the non-negligible inclination angle of NGC 5427. Otherwise the observed motions are consistent with what would be expected by corrugation in the velocity field of the gaseous disk induced by a hydraulic jump around the spiral arms.

4. A follow-up program

Here we have presented some results evidencing the role of the corrugation studies as key clues for understanding the large-scale mechanisms that arrange and organize the ISM in disk galaxies. Otherwise, the discussed models suggest some corrections to the way of deriving distances from kinetic data, if we want to get a more realistic view of our own Galaxy.

The actual models have a number of numerical simplifications as well as omission of physical processes (Gómez & Cox 2002; Franco et al. 2002a). Several works to improve these models are actually in progress in our group. Further 2D and 3D studies including other important ingredients, such as self-gravity, molecule formation, gas flow with correct pitch angle, differential rotation, heating and cooling of the gas and cosmic rays, will shed more light on the actual 3D structure of galactic disks.

Concerning the observational aspects, a more realistic description of the gaseous disk structure in the Milky Way will come from the detailed analysis of the new HI and CO surveys (some of them in progress). Overall, if 3D galactic dynamics is taken into account to derive the kinetic distances, GAIA will be the main information source for the stellar component of our Galaxy. Detailed kinetic patterns of young stellar systems at large galactocentric radius could be analyzed and compared with the gas component. The temporal history of the spatial and kinetic corrugations would provide important clues about how the star formation modifies the initial structure of the gas and on the effects of energy injection into the system.

For external galaxies the situation is different, only face-on objects are useful to our aims. No spatial information is expected from the study of this sample, excepting *meandered* patterns (Sánchez-Colín 2002). On the contrary 2D radial velocity maps at different wavelengths should help to detect and analyze the vertical velocity corrugations. The difference with previous situation is that now we know how and what to search for.

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References

Alfaro E.J., Cabrera-Caño J., Delgado A.J., 1991, ApJ, 378, 106

Alfaro E.J., Cabrera-Caño J., Delgado A.J., 1992a, in The Stellar Populations of Galaxies, IAU Symp. 149, ed. B. Barbuy & A. Renzini, Dordrecht: Kluwer Academic Pub., 386

Alfaro E.J., Cabrera-Caño J., Delgado A.J., 1992b, ApJ, 399, 576

Alfaro E.J., Pérez E., González Delgado R.M., Martos M.A., Franco J., 2001, ApJ, 550, 253

Alfaro E.J., Efremov Yu.N., 1996, RMxAA(SC), 4, 1

Arp H.C., 1964, ApJ, 139, 1045

Avedisova V.S., 1989, Astrophysics, 30, 83

Beck R., Loiseau N., Hummel E., Berkhuijsen E.M., Gräve R., Wielebinski R., 1989, A&A, 222, 58

Berdnikov L.N., Efremov Yu.N., 1993, Astron. Lett., 19, 389

Boulares A., Cox D.P., 1990, ApJ, 365, 544

Cox D.P., 2002, RMxAA(SC), 9, 14

Dixon M.E., 1967, MNRAS, 137, 337

Edelsohn D.J., Elmegreen B.G., 1997, MNRAS, 287, 947

Efremov Yu.N., 1978, Soviet. Astr. Letters, 14, 347

Elmegreen B.G., Elmegreen D.M., 1983, MNRAS, 203, 31

Elmegreen B.G., Emegreen D.M., 1986, ApJ, 311, 554

Florido E., Battaner E., Prieto M., Mediavilla E., Sánchez-Saavedra M.L., 1991, MNRAS, 251, 193

Franco J., Martos M., Pichardo B., 2002a, in Disk of Galaxies: Kinematics, Dynamics and Perturbations, eds. E. Athanassoula & A. Bosma, ASP Conference Series, in press

Franco J., Kim J., Alfaro E.J., Hong S.S., 2002b, ApJ, 570, 647

Franco J., Santillán A., Martos M., 1995, in The Formation of the Milky Way, eds E. J. Alfaro & A. J. Delgado, (Cambridge: Cambridge University Press), 97

Fridman A.M., Polyachenko V.L., 1984, Physics of Gravitating Systems, New York: Springer, vols. 1 and 2

Gómez G., Cox D.P., 2002, ApJ, 580, 235

Gum C.S., Kerr F.J., Westerhout G., 1960, MNRAS, 121, 132

Kerr F.J., 1957, AJ, 62, 93

Kim J., Hong S.S., Ryu D., 1997, ApJ, 485, 228

Kim J., Hong S.S., 1998, ApJ, 507, 254

Kim J., Franco J., Hong S.S., Santillán A., Martos M.A., 2000, ApJ, 531, 873

Kolesnik L.N., Vedenicheva I.P., 1979, A&A, 76, 124

Larson R.B., 1988, in Galactic and Extragalactic Star Formation, eds. R. E. Pudritz & M. Fich (Dordrecht: Kluwer), 459

Lockman F.J., 1977, AJ, 82, 408

Malhotra S., 1995, ApJ, 448, 138

Martos M., Cox D.P., 1998, ApJ, 509, 703

Martos M., Allen C., Franco J., Kurtz S., 1999, ApJ, 526, L89

Mouschovias T., Shu F., Woodward P., 1974, AA, 33, 73

Nelson A.H., 1985, MNRAS, 215, 161

Parker E.N., 1966, ApJ, 145, 811

Quiroga R.J., 1974, A&SS, 27, 323

Roberts W.W., 1969, ApJ, 158, 223

Sánchez-Colín A., 2002, Master Thesis, University of Granada, Spain

Santillán A., Franco J., Martos M., Kim J., 1999, ApJ, 515, 657

Schmidt-Kaler Th., Schlosser W., 1973, A&A, 25, 191

Sparke L., 1995, ApJ, 439, 42

Spicker J., Feitzinger J.V., 1986, A&A, 163, 43