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ON THE NATURE OF THE VERTICAL STRUCTURE OF THE GALACTIC DISK

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RESUMEN

El disco galáctico presenta desviaciones sistemáticas respecto al plano formal de simetría conectadas con regiones de formación estelar. En este trabajo revisamos los diversos mecanismos capaces de generar estas estructuras, haciendo especial énfasis en el papel que las nubes de alta velocidad pueden estar jugando en el desarrollo de los complejos de formación estelar y en la inducción de las corrugaciones.

ABSTRACT

The galactic disk presents systematic deviations with respect to the formal galactic plane related to star-formation regions. In the present paper we review the different mechanisms capable of generating these structures, stressing the role which high-velocity clouds (HVCs) may play in the development of star-formation complexes and their possible involvement in the generation of the corrugations.

Key words: **GALAXY – STRUCTURE**

1. INTRODUCTION

The young stellar component and gas of the Galactic disk show systematic displacements from the formal galactic plane. In the inner regions of our Galaxy the so-called corrugation appears to dominate the vertical structure of the galactic disk. This phenomenon, which could be defined as a residual wavy structure with respect to the defined mean plane (Gum, Kerr, & Westerhout 1960; Lockman 1977; Spicker & Feitzinger 1986; Alfaro, Cabrera-Caño, & Delgado 1992a), has been observed throughout the different spiral arms and galactocentric radial directions (Spicker & Feitzinger 1986; Malhotra & Rhoads 1995).

This phenomenology has also been observed in other galaxies (Florido et al. 1991) which would seem to indicate the universality of these kinds of structures. Recent infrared studies appear to indicate that old stars show similar displacements to those found in the young galactic component, which in turn suggests that they might be of gravitational origin (Djorgovski & Sosin 1989; Rhoads 1995). The amplitude and scale of the corrugations show a wide range of values (50–150 pc in amplitude and 1–13 kpc in scale), depending as much on the spiral arm as on the different spiral tracers chosen for their study (Spicker & Feitzinger 1986; Florido et al. 1991).

Besides these large-scale features, the interstellar medium also shows local deviations from the formal plane, referred to in the literature as chimneys, bubbles, holes and worms (Heiles 1984, 1989; Li & Ikeuchi 1990). These structures seem to arise from local star–gas interactions and show no large-scale patterns.

The gas and young stellar population used in most of these studies also provide the observational basis for studying star-formation processes and for determining the locations and scales of the star-formation regions in our Galaxy and others (e.g., Efremov 1978; Efremov & Sitnik 1988; Elmegreen & Elmegreen 1983). Star formation seems to occur on all scales with a hierarchic pattern generated and controlled by self gravity and turbulence (Elmegreen & Efremov 1996). Only in galaxies with strong density waves does the gas become structured by regular forces, and supercomplexes appear as the dominant, largest scale of star formation. Our Galaxy provides us with several examples of large-scale star-formation regions. In grand-design spiral arms, such as Carina–Sagittarius, the density waves seem to control the pattern of star formation, leading to the generation of typical supercomplexes arranged along the whole arm, whereas the Orion–Cygnus arm could have been generated by the balance between turbulence and shear.

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Spicker & Feitzinger (1986) analyzed the H I centroid distribution of the galactic spiral arms, finding three different corrugation scales. The short corrugation scale ($\lambda \approx 1$ kpc) is coincident with the scale properties of turbulence and magnetic fields in the Galaxy (Spicker & Feitzinger 1984; Hanawa 1995). Thus, vertical deviations of the galactic disk and star-formation activity could be inter-related in some way.

Previous hints about the connection between vertical structure and star-formation probes can be found in Quiroga (1977), Kolesnik & Vedenicheva (1979), and Schmidt-Kaler & Schlosser (1973). Alfaro, Cabrera-Caño, & Delgado (1991) studied the three-dimensional distribution of young open clusters in a radius of 3 kpc around the Sun, and found a valley-peak pattern where four star-forming supercomplexes (Efremov & Sitnik 1988) appear to be associated with the valleys of the distribution. These authors detected the existence of a large depression in the third Galactic quadrant associated to the supercomplex S III, which they called Big Dent.

The vertical structure of the disk as determined from the distribution of Cepheid stars (Berdnikov & Efremov 1993) supports the existence of this depression, although with a minimum of $Z \approx -50$ pc, which is *lower* than the value of $Z \approx -150$ pc found by Alfaro et al. (1991).

The molecular clouds of the first galactic quadrant also exhibit a striking pattern in their vertical distribution. The molecular clouds associated with the Sagittarius and Scutum arms show a mean displacement in Z of −20 pc with respect to the clouds located in the interarm region (Sanders, Solomon, & Scoville 1984).

The similarity between the largest scale of star formation (supercomplexes) and the short corrugation scale, as well as the spatial coincidence of large star-forming regions with the valleys of the vertical structures in the solar neighborhood, suggests that the dynamic processes involved in the formation of peaks and valleys should be intimately associated with those producing complexes of gas and the consequent zones of active star formation. Here we shall discuss certain peculiar star-formation regions and the different mechanisms able to generate the complicated Z-structure observed in the galactic disk.

2. CORRUGATION CENTERS

Analysis of the three-dimensional distribution of young galactic clouds in the solar neighborhood reveals the existence of a large depression, with a maximum depth of 150 pc, covering an extensive area ($\approx 1.5 \times 2$ kpc^2) of the third galactic quadrant. Further indicators of recent star formation, such as WR stars, would support the existence and magnitude of this depression (Alfaro et al. 1992b). Clouds of CO located in this quadrant, with estimated distances which seem to imply that they are clearly related to this structure, also show that the molecular component is mainly located below the formal galactic plane (May, Murphy, & Thaddeus 1988; Sodroski 1991).

Estimates of the mass of the stars and gas involved in this displacement are in excess of 10^7 solar masses (Alfaro et al. 1991), and the minimum energy needed to displace 10% of the mass 150 pc below the galactic plane is more than 5×10^{51} erg. The linear scale of this structure, its depth, and the mass and energy ranges involved in this displacement would make it difficult to fit it into a single *universal* corrugation pattern.

There are indications of the existence of other depressions in the Milky Way, which are in some aspects similar to the Big Dent. Orsatti (1992) analyzed a sample of distant ($d > 3$ kpc) OB stars in the southern hemisphere, and found that a group of stars in the direction of Puppis, near the cluster NGC 2439 ($d = 4.4$ kpc), is located below the galactic plane. She also pointed out the possible existence of a Z–age gradient in which the youngest stars are the farthest from the plane. Three Cepheid stars lie in the neighborhood of this cluster, with a period–Z relation which would support the existence of a gradient in the same sense as that shown by the OB stars. However, it would be rash to jump to conclusions about whether this group of stars indeed forms an isolated structure (such as the Big Dent) or is rather no more than a manifestation of the galactic warp. In any event, the existence of a correlation betwen Z and age in this group of stars coincides with the findings in the Big Dent, and may be explained by an HVC–disk collision model (Cabrera-Caño et al. 1995).

The three-dimensional distribution of the Cepheid stars in the solar neighborhood (Berdnikov & Efremov 1993; Alfaro, Cabrera-Caño, & Efremov 1996) shows certain striking features. The deepest, and rather dense, concentration of Cepheid stars appears located close to —but not in the same position as— the very center of the Big Dent. This group of Cepheids presents similar periods, indicating a narrow age spread. Another group of Cepheid stars appears closer to the Big Dent's center, also presenting negative Z-values and similar periods. The existence of Cepheid-star concentrations with similar periods within the structure of the Big Dent may be interpreted as the result of local star-formation processes triggered by the HVC–disk collision.

Even more telling than the above arguments is Fig. 3 of Florido et al. (1991), which shows the vertical profile of the galaxy NGC 4244 in the U and Hα bands. This figure also shows a deep valley located before the start of the opposite-sign (i.e., upward) warp. As these authors comment, "a more precise description would be that a zone of higher perturbation exists".

Thus, the depressions found in our own Galaxy appear to have counterparts in other galaxies, and are not directly related neither the corrugation pattern nor the warp. In the words of Florido et al. (1991), they appear to behave as "the corrugation centers" out of which this perturbation radiates.

3. VERTICAL OSCILLATIONS

Gravitation and magnetic field seem to be the most likely candidates for having caused the deviations observed in the stellar and gaseous component of the galactic disk.

The magnetic field has been very much to the fore over the last years, and has joined the set of models which can be used to explain such chronic galactic puzzles as the galactic warp (Binney 1992; Battaner 1995) or the maintenance of the rotation curve in the outermost regions of the Galaxy (Battaner et al. 1993). Models of the instabilities of the galactic disk caused by magnetic fields and self-gravity produces periodic structures with maximum densities of displaced gas with respect to $Z = 0$, with a characteristic wavelength of ≈ 1 kpc (Hanawa, Nakamura, & Nakano 1992; Hanawa 1995). These results appear to roughly match the pattern of corrugation observed in our Galaxy (Spicker & Feitzinger 1986) and the location of the star-formation complexes detected in the Carina–Sagittarius arm (Avedisova 1989; Alfaro et al. 1992a; Efremov 1995). However, they do not seem able to explain the origin of the large (in terms of both extension and depth) depressions observed in our Galaxy and others.

Nelson & Matsuda (1980) analyzed the behavior of non-linear corrugation waves in the gas disk of a spiral galaxy, assuming that the global morphology of the corrugations is spiral. This paper predicts the existence of a corrugation which is singly periodic in azimuth and doubly periodic for the gas density, and also indicates a possible common origin for the corrugations and the warp.

The perturbations of the potential might have been caused either by the tidal distortion produced by the passage of a neighboring galaxy or by the dynamic pressure of an intergalactic gas through which galaxies move. However, these hypotheses which purport to explain the generation of the corrugations do not appear to be supported by subsequent analysis.

Weimberg (1991) studied the vertical oscillation of the galactic disk, and found that the oscillations corresponding to wavelengths of the order of 10 kpc could be excited by the passage of dwarf galaxies and maintained for a long period of time. Yet higher order frequencies do not appear to be easily excited by a large-scale perturbation and, as this author pointed out, the effect of small-scale perturbations needs to be investigated.

Thus, while the Parker–Jeans instabilities would not seem to be the most likely mechanism to have generated such "large depressions" as the Big Dent or the one observed in NGC 4244, the gravitational interaction between our Galaxy and its satellites proves to be inefficient when it comes to producing undamped waves of high frequencies, such as the corrugations observed in the Milky Way and other galaxies (Weimberg 1991).

The observational properties of the Big Dent indicate that any formation model for this structure requires the identification of the mechanical energy source capable of producing this massive displacement of the galactic disk. The required energy ($> 5 \times 10^{51}$ erg) could be obtained from stellar winds and supernova explosions in OB associations (McCray & Kafatos 1987) or from collisions of high velocity H I clouds with the galactic disk (Tenorio-Tagle et al. 1980; Franco et al. 1988). It is very difficult to explain the high degree of asymmetry and the large size shown by the Big Dent by an isotropic mechanism such as the supernova explosions and/or strong stellar winds. In order for this mechanical energy source to be considered as being responsible for this displacement, new "ad hoc" assumptions—such as an unknown collimation process—must be introduced.

The singularity of this structure, together with its universal character, led us to propose a collision between a high-velocity cloud and the galactic plane as the most likely mechanism to have produced these displacements, while creating conditions in the gas which were ideal for massive star formation to occur. The original idea about a collision between a high-velocity cloud and the galactic plane possibly having created active star-formation regions which were displaced with respect to the formal galactic plane can be credited to Tenorio-Tagle (1980) and Tenorio-Tagle et al. (1986, 1987), who modeled these types of events, explaining the location and internal structure of the Orion and Monoceros complexes (Franco et al. 1988). However, our proposal is not restricted to the role of such events in the generation of singular star-formation regions, but also considers their possible involvement in producing the large-scale vertical pattern of the galactic disk (Alfaro et al. 1992a).

4. HALO–DISK INTERACTIONS

Danly (1995) has recently reviewed the nature of Milky Way halo gas and its role in the evolution of the galactic interstellar medium via the cycling of energy and enriched material through the Galaxy. For several years, the Galactic Fountain model and its derivatives have been considered as the best theory for explaining the origin and observed properties of the halo gas (Shapiro & Field 1976; Bregman 1980; Shapiro & Benjamin 1993 among others).

Recent observations of the distribution of high-velocity clouds in the Milky Way (Danly 1992) and other galaxies (Kamphuis 1993) seem to be less easily explained in the context of the Galactic Fountain model. These include:

a) The anisotropy observed in the distribution of the infalling clouds in our Galaxy is difficult to understand in the context of a quasi-steady-state fountain model—particularly considering that the phenomenology of the worm distribution seems to be more numerous and isotropic than that presented by the HVCs.

b) ROSAT X-ray observations show clear variations of X-ray emission in regions with identical values for the H I column density (Snowden et al. 1994). These observations do not appear to support the existence of a hot "corona" in the halo generated by a quasi-steady-state Galactic Fountain (Spitzer 1956).

c) The relationship between Z and the cloud velocity in the northern hemisphere shows an opposite trend to that which is to be expected from a model in which the gas was accelerated upward from the disk and was now falling back. Most of the clouds show higher (infalling) velocities at larger Z (Danly 1992).

d) Analysis of the HVCs in NGC 6946 shows a velocity range with respect to the systemic velocity of the galaxy of between 30 and 90 km/s, which is somewhat lower than the velocity range of the HVCs in the Milky Way. The size and kinetic energy of these clouds ranges between 1 and 15 kpc in diameter and 10^{53} and 10^{54} erg, respectively (Kamphuis 1993). The largest of them (Nr. 2 in Kamphuis 1993) does not present a clear counterpart in the H I hole distribution in the galactic disk. Thus, although we believe that most of the HVCs in the galaxy may have originated in the disk, via stellar winds and clustered supernova explosions, there do seem to be several examples which are difficult to explain by means of these mechanisms.

This observational data set seems to suggest that if these clouds do have their origin in the galactic disk, then they would be more likely to have been generated in highly energetic episodic events than in an ubiquitous steady-flow of material. Nevertheless, we do not have sufficient grounds for rejecting out of hand an extra-disk origin for these gas clouds.

New ideas about the formation of the Milky Way point toward a more chaotic origin for the formation of the halo (Searle & Zinn 1978; Zinn 1993). In this model, the protogalactic material might have been formed by various smaller-sized clouds, some of which accreted to form the bulk of the halo and disk of the Milky Way, while the others might have evolved individually, giving rise to the formation of independent stellar systems orbiting around the galactic center. These subsystems would have had different evolutionary clocks and their subsequent accretion by the Galaxy would explain the observation of stellar objects whose kinematics, chemical composition and spatial distribution are not compatible with a monolithic model of the formation of the Milky Way (Suntzeff, Kinman, & Kraft 1991; Preston, Shectman, & Beers 1991).

Preston, Beers & Schectman (1994) found signs of the accretion of a metal-poor object in which star formation had occurred up until recently (a few Gigayears). The newly-discovered Sagittarius dwarf (Ibata, Gilmore, & Irwing 1994) may be in the process of merging with the Galaxy's disk. It therefore seems reasonable to assume that at least some of the HVCs we observe in our Galaxy were formed in the gas of the "protogalactic subsystems", attracted by the tidal forces of the Galaxy. Mirabel & Morras (1990) pointed out that the Magellanic stream could be a possible source of the galactic HVCs. Dwarf galaxies such as Carina and Sagittarius are also possible candidates for the origin of these events.

Our Galactic disk is not a closed system, and the halo–disk interaction is continuously modifying the physical properties of the disk (e.g., Mirabel 1991; Larson 1993). The exchange of mass and energy between the halo and the disk (in both directions) should largely affect, among other things, the chemical evolution, the rate of star formation, and the dynamic and spatial structure of the disk. In this way, HVCs can be considered as the transmission vectors for this exchange.

5. CONCLUSIONS

Regardless of the origin of the HVCs (Galactic Fountain or extra-disk source) it certainly looks as though any scenario, attempting to explain the dynamic and spatial structure of the galactic disk and its involvement in the star-formation processes occurring within it, ought to include this source of energy and matter. The results of Kamphuis (1993) show the existence of a reserve of mass and energy in the gas of the halo of some spiral galaxies of the order of a few 10^8 solar masses and $10^{54} - 10^{55}$ erg, respectively.

Several authors (Franco et al. 1988; Comerón & Torra 1992; Lepine & Duvert 1994) have modeled the collision of HVCs with the galactic disk in order to explain the origin of different star-forming regions which present peculiar structural characteristics (Gould's Belt) or which are located beyond the galactic plane (Orion and Monoceros). This model has also been invoked to reproduce the location and properties of the Perseus complex (Phelps 1992) and the Big Dent (Alfaro et al. 1991; Cabrera-Caño et al. 1995).

In addition, the vertical disturbance, on being transmitted in the medium, may excite the generation of high-frequency waves, giving rise to the corrugations observed in this and other galaxies. The observational results and arguments presented in this paper suggest that catastrophic events, such us HVC–disk collisions, play a fundamental role in various phases of the process chain called star formation. Perhaps we should entertain the idea that a large-scale vertical pattern and its associated star formation is driven by at least two interrelated mechanisms acting on different scales: on the one hand, a more local, catastrophic and unpredictable mechanism—such as the one which might have produced the Big Dent—and on the other, a more global and deterministic mechanism, resulting from the response of the galactic disk to vertical disturbances.

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