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SOME THEORETICAL CONSEQUENCES OF THE THICK, MAGNETIZED GALACTIC DISK

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RESUMEN

Numerosos estudios observacionales recientes revelan un nuevo paradigma de galaxias de disco, uno en el cual capas de gas tibio ionizado, estructuras de polvo y campos magnéticos son comunes a alturas considerables (de kpc) del plano medio galáctico. Este disco grueso posee una estructura intrincada y aún pobremente conocida. Su consideración en el modelaje de procesos dinámicos de gran escala en el medio interestelar, tales como la interacción de nubes de alta velocidad con discos galácticos, la inestabilidad de Parker, y la respuesta del gas a la onda de densidad espiral, altera considerablemente los resultados "clásicos" obtenidos para discos galácticos delgados supuestos en estudios previos.

ABSTRACT

A number of recent observational studies reveal a new paradigm for disk galaxies, one in which layers of warm ionized gas, dust structures and magnetic fields commonly extend to considerable heights (of kpc) above their midplanes. This thick disk has an intricate and largely unknown structure. Its inclusion while modeling large scale dynamical processes in the interstellar medium, such as the interacion of HVC with galactic disks, the Parker instability, and the gas response to the spiral density wave, alters considerably the "classic" results obtained in the thin disk picture of galactic disks which was popular in previous studies.

Key Words: **GALAXY: HALO — GALACTIC: STRUCTURE — MHD**

1. INTRODUCTION AND OBSERVATIONAL MOTIVATION

In spiral galaxies, the diffuse interstellar medium is akin to an atmosphere: a thick layer of cosmic rays, magnetic fields, dust and gas structures extending to z heights of 1 kpc or more above the disk midplane. Many previous theoretical results for large scale processes in the ISM – examples are the gas response to the spiral density wave (SDW), the Parker instability, or the interaction of high velocity clouds (HVC) with the disk – were obtained in galactic models that did not consider the vertical thickness z, or in which that thickness was assumed to be restricted to a thin disk of approximately 100 pc on a side (following Spitzer 1978). Now we know (see below) that above the dense midplane cloudy gas, there are significant amounts of diffuse warm ionized gas at heights at which a given parcel has a higher weight than the same parcel located at low z. This fact, due to the increasing gravity as a function of [z] at a given position in the midplane, confers to the atmosphere interesting dynamical properties: the equilibrium suggested by the data, with local measurements of pressure providing useful boundary conditions, is delicate. Compressibility of the layer is greatly affected by magnetic pressure, which appears to be in rough equipartition with turbulent and cosmic–ray pressure. Thermal pressure is probably a minor contribution to the total pressure, except in localized regions or on top of the atmosphere. In this thick, magnetized and pressurized layer, momentum transfer via wave propagation is favored over mass transfer in long length scales. Also, the rigidity provided by the field leads to water–like behavior in the gas response to the SDW. The disk is prone to form extraplanar gas structures, from which new stars can be formed at high galactic latitudes.

In our Galaxy, the observational basis for the picture described above should be traced to Hoyle & Ellis (1963), who detected the warm ionized gas in absorption against the Galactic synchrotron background.

However, the existence of this diffuse layer did not gain recognition for many years. It was identified by Reynolds (1989) as H II at a likely temperature of 8000 K, with a scaleheight close to 1 kpc, and subsequent studies confirmed the detection in Hα and nebular lines. This gas constitutes an outstanding problem; its surface density is one third that of the HI, and the power requirements for its ionization are formidable, equivalent to the total Galactic supernova power.

Assembling a large set of data for our Galaxy, including the HI extended layer with a scaleheight of 400 pc (Lockman, Hobbs & Shull 1986), cosmic rays and magnetic fields, the synchrotron background and Faraday rotation studies, Boulares & Cox (1990) found that these observations are consistent with a gaseous Galactic disk in a time–averaged hydrostatic equilibrium. The inclusion of magnetic tension saves all possible observational constraints, and pressure must drop with [z] more slowly than density does.

Recent observations indicate that thick disks of diffuse ionized gas are common in external galaxies (Rand 1997; Rand, Kulkarni & Hester 1990). Magnetic fields have been traced to several kpc above the midplane in these edge–on galaxies (Hummel & Beck 1995).

The correlation of extraplanar dust and Hα at high z found in nearby edge–on spirals by Howk & Savage (1999) firmly establishes the vertical extent of galactic disks (the dust structures lie at $z \gtrsim 0.4$ kpc). NGC 891 is a well studied example. Dust–bearing clouds were traced in BVI images (Howk & Savage 2000) to heights close to 2 kpc, and highly structured features to higher z. Although dust and the diffuse ionized gas in Hα coexist in the thick disk, they may not be physically connected; the diffuse gas is more smoothly distributed than the dusty features. Further evidence for high–z H II regions ($0.6 < z < 1$ kpc) in other galaxies has been reported by Walterbos (1991), and Ferguson, Wyse & Gallagher (1996).

Returning to our Galaxy, high–latitude molecular clouds have been found (e.g. Blitz 1991), as have massive star–forming clouds and a large structure delineated by young stars off the disk's midplane (respectively, the Orion and Monoceros cloud complexes, see Franco et al. 1988; and the Big Dent, see Alfaro, Cabrera–Caño & Delgado 1991). In general, conditions at $z \gtrsim 1$ kpc are poorly known; the filling factor of hot gas and even the most quoted model of the ISM, that of McKee & Ostriker (1977) are under debate (Cox 1995). Kinematically, the upper layers are observed to contain material in large–scale structures frequently with downward velocities. The H I arch, which covers a large fraction of the northern Galactic polar region, is a good example, falling at 40 km s^{-1} (Kuntz & Danly 1996). HVC clouds seem to suggest that the layers are being compressed. Towards halo stars, UV absorption line studies (Tripp, Sembach & Savage 1993; Spitzer & Fitzpatrick 1993), as well as other H I and optical surveys reveal "forbidden" velocities (inconsistent with a simple model of galactic rotation). In particular, the 21–cm emission profile toward the halo star HD93521 of Spitzer & Fitzpatrick (1993) is bimodal, with broad, featured components indicating concentrations of mass in the velocity space, at 0 and -50 km s^{-1}. It is worth noticing that the features may not be spatially correlated (velocity crowding), as discussed in Martos & Cox (1998). General vertical motions in H I have been reported for a long time, in some cases seemingly associated to spiral arms (Sofue & Tosa 1974).

Martos (1993) built thick disk models based upon the observational account given by Boulares & Cox (1990). The models are in magnetohydrostatic equilibrium and have interesting dynamical properties which update results for several large scale dynamical processes in the galactic ISM. In the next section, some theoretical consequences of the thick disk are examined in light of recent numerical simulations of such processes, and briefly discussed in the context of the observations described above.

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2. THEORETICAL RESULTS IN A THICK GALACTIC DISK

1) *The Gas Response to the SDW: A Galactic Bore*

Martos & Cox (1998) revisited the problem of the gas response to the SDW in the thick disk model of Martos (1993). The results alter the conventional view of the SDW scenario for star formation, obtained in thin or zero–thickness disks: whereas marked density enhancementes still occur in the midplane, the shock and a prominent high column density structure extend to high z above the spiral arm. The structure has both the characteristics of a hydraulic jump, or bore, and a shock. Thus if the SDW action triggers molecular cloud and star formation, it should do so not only at the midplane but also at z well above the star–forming disk of the conventional picture (Martos et al. 1999). The numerical calculations, performed with the code ZEUS (see Stone & Norman 1992a; 1992b), showed that gas entering the spiral arm (upstream) rises suddenly, shocks above the arm, then feeds the front with denser material than usual at a [z] range of 500 to 800 pc,

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where conditions become favorable for molecular cloud and star formation. There is a large downfall region downstream the arm. Because the ascent is rapid, at any given time more gas is falling than rising. How does this scheme match the observations? 1. The downfall of cold gas is commonly observed (Kuntz & Danly 1996). 2. There is an anomalous group of early–type —and hence mostly young— stars (Lance 1988), and also a group of apparently normal main–sequence OB stars (Saffer et al. 1997) far from the midplane, and their lifetimes are too short to explain their position if they were formed in the Galactic plane – formation in situ is inescapable for a number of them. 3. There is a population of molecular clouds at high [z] in our Galaxy (Blitz 1991). Although data for the NGC 457 cluster indicates that it was formed from a molecular cloud at least 500 pc from the plane, that conclusion still needs confirmation from proper motions. The Draco cloud has an estimated $z > 500$ pc (Georigk & Mebold 1986). G135+551 has the highest radial velocity of all, -45 km s^{-1} (Heiles, Reach & Koo 1988). This velocity is very close to our prediction for the downfall of gas after the cloud is formed past the shock front. 4. A recent Hα emission line study from NGC 5427 (Alfaro et al. 2000) revealed a radial corrugation in the velocity field of this nearly face–on spiral. There are peak blueshifted velocities upstream of three arm segments, and the corresponding redshifted velocities downstream of the arms, in agreement with the galactic bore picture.

2) *The Interaction of HVC with Galactic Disks*

The present data for HVC indicate an excess of negative velocities (infall) over positive ones. The interpretation for their origin and evolution is unclear because their distances and tangential motions are unknown (Wakker & van Woerden 1997). However, observational signatures for interactions of HVC's with galactic disks have been claimed. Examples are the complexes AC and H, near the anticenter direction (e.g. Mirabel 1981), or in M101 (van der Hulst & Sancisi 1988) and NGC 4631 (Rand & Stone 1996). Previous numerical simulations with non–magnetic and thin disks (for instance Tenorio–Tagle et al. 1986, 1987; Franco et al. 1988; Rand & Stone 1996) resulted in structures with sizes of hundreds of pc, massive structures far from the midplane and even holes drilled through the midplane, venting gas into the other side of the disk.

We performed 2D numerical simulations with ZEUS in our thick, magnetized disk model (Santillán et al. 1999) of HVC clouds falling from different z locations into the Galactic midplane. With the magnetic field lines parallel to the midplane and in the plane of motion, magnetic tension is put to work and the clouds cannot reach the central plane. Oscillations on both sides of the disk are induced. It is so that the magnetic field inhibits mass exchange, but provides an adequate coupling for energy and momentum exchange between the disk and the halo via MHD (and particularly magnetosonic) waves. Aspects of this shielding by a pressurized cushion could apply to the 3D general case and to other energetic events, such as galactic fountains or superbubble expansion.

3) *The Parker Instability*

We have recently worked out the linear analysis (Kim et al. 2000), and followed the nonlinear evolution with two different MHD codes (Santillán et al. 2000) of the Parker instability in our thick, multicomponent disk model and under a realistic gravity matching the observations of Bienaymé, Robin & Crézé (1987). There are substantial differences in our results in comparison with previous galactic calculations of this process, which assumed thin disks, and the linear gravity corresponding to the low [z] regime in the gravitational field provided by the stars: the fastest growing mode has a wavelength close to 3 kpc, and a growth time of the order of 30–60 Myr. These numbers are much larger than those from thin disks analyses, and suggest further examination of the role of the instability in the formation of giant molecular complexes (Mouschovias, Shu & Woodward 1974) . If the instability is triggered by the SDW, our result contrasts with the commonly accepted thin disk wavelength of 1 kpc. A step forward in connection with the SDW is the work of Franco et al. (in preparation), who examined the optical segment of the Carina–Saggitarius arm and performed 3D simulations of the instability. This allows both modes, the undular (the 2D originally studied mode by Parker 1966) and the interchange mode to act simultaneously. The former appears later but dominates the evolution inside the arm, creating large gas concentrations along the arm that are antisymmetric with respect to the midplane, thus a corrugation of the arm, on a lengthscale of 2.4 kpc. The interchange mode forms small structure in the interarm region.

4) *Wave Propagation into the Galactic Halo*

Walters & Cox (2000) have modeled vertical disturbances in the interstellar medium using a similar thick disk model as the one cited above. With 1D simulations, they aimed to explain four observational phenomena: the falling sky in the northern hemisphere, the nature of "clouds" in absorption spectra, the structure of spiral arms, and the abundance of high stage ions far off the plane of the galaxy. They studied the response of the thick disk to disturbances imposed as displacements of the midplane, following the propagation of small waves as well as large perturbations from energetic events in the midplane. They found that three of the four observations are closely connected: with the simple existence of a strong local compression, then an expansion, the dense material near the plane falls back rapidly (in the harmonic oscillator regime), whereas the rarified material on top takes longer in falling upon the dense layer. The observed velocity segregation is reproduced in a bounce time of 50 Myr after the event. Oscillation at the resonant frequency of the fundamental breathing mode results in a substantial amplitude, creating a hot galactic halo. The initial compressions in spiral arms may result in structuring the arms through further oscillations. Finally, the propagation of small waves into the halo creates features in absorption spectra usually interpreted as clouds. They appear as a consequence of velocity crowding, with no associated density enhancements along the line of sight.

3. CONCLUSIONS

The inclusion of the thick, magnetized galactic disk in theoretical modeling of the ISM substantially alters previous conceptions of every dynamical process here considered. Some aspects of this modeling should and are already observable. The magnetized thick disk acts as a shield of the inner disk, but is also prone to form dense vertical structures extending from the midplane in the presence of even small amplitude disturbances, which reminds us of the extraplanar dust and structure observed in our Galaxy and other spiral galaxies. The formation of molecular clouds and stars at high [z] are possibly a direct consequence of this fact. Also, the extra degree of freedom from the vertical direction channels gas motions which could not be explored in modeling based on thin disks and that seem consistent with the observed kinematics at high galactic latitudes. The layer has normal modes of motion that can simply reproduce some basic pieces of such kinematics, as a result of perturbations to be expected in the ISM, such as the SDW, a secular process in disk galaxies, or explosive events from OB associations. But even small amplitude perturbations will lead to the growth of high frequency waves with height, creating large velocities in the higher layers and a hot outer halo, which the thick disk has a tendency to develop, either by the continuous injection of these waves or a shock propagating upwards from a large event. Featured spectra should not be interpretated only as the signature of absorbing clouds. It is very easy to obtain such spectra from waves, or large–scale regions of coherent motion in an initially homogeneous gas distribution. If the disk is Parker unstable, the wavelenghts of maximum growth are about three times longer than those corresponding to a thin disk for the undular mode.

Much more modeling, particularly in 3D, is needed. It can be anticipated, however, that rapid motions of gas and large–scale structures at high z, vertical sheets and ridges of material extending from the central disk, apparent differential rotation between layers in the stratified galactic “atmosphere”, and large–scale flux tubes (ropes) and turbulence into the medium are all aspects that must be considered in the upcoming models.

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