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STAR FORMATION IN A MAGNETIZED DISK

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RESUMEN

La conexión entre la formación estelar y las inestabilidades de discos ha sido un problema abierto durante décadas. Tanto las observaciones como la teoría han demostrado que las leyes empíricas que relacionan a la formación estelar con otros fenómenos ligados a la autoregulación del proceso, se pueden explicar despreciando el magnetismo por completo. En este trabajo, a partir de la relación de dispersión para modos sin simetría axial y otros argumentos, buscamos demostrar la relevancia de los campos magnéticos para la formación estelar a escala galáctica en protodiscos masivos y espirales normales. Se concluye que los trabajos recientes que sugieren que los campos magnéticos son responsables del origen de la secuencia de Hubble aun no tienen fundamento teórico.

ABSTRACT

The connection between star formation and disk instabilities has been an outstanding problem for decades. Surprisingly, both observations and theory have shown that empirical laws of star formation and other phenomena concerning self-regulation of star formation in disks can be explained neglecting completely magnetism. From the dispersion relationship for non-axisymmetric modes and other arguments, we aim to show here the relevance of magnetic fields for galactic-scale star formation in normal spirals and massive protodisks. It is concluded that recent claims that suggest magnetic fields as being responsible for the origin of the Hubble sequence have not any theoretical support yet.

Key Words: **GALAXIES : FORMATION — GALAXIES : MAGNETIC FIELDS — GALAXIES : SPIRAL — ISM : MAGNETIC FIELDS**

1. INTRODUCTION

Star formation in disks appears to be self-regulated. Understanding the parameters that control star formation is intimately related to self-regulation mechanisms, which are of great importance in the theories of galaxy evolution. The connection between star formation and disk instabilities was originally envisioned by Goldreich & Lynden-Bell in 1965. The stability parameter for a gas disk, $Q = \kappa v_{\rm t}/\pi G\Sigma_{\rm g}$, where $\Sigma_{\rm g}$ is the gas surface density, $v_{\rm t}$ the effective turbulent velocity and κ the epicyclic frequency, has received a lot of attention as an important parameter for star formation, following Kennicutt's suggestion that galaxy disks have star formation where Q is less than a certain critical value Q_0 (Kennicutt 1989). The proposed scenarios to explain such a connection rely on semiphenomenological arguments ignoring the microphysics of star formation. Unexpectedly, the gas Toomre parameter appears to be much better related with star formation than any other more sophisticated indicator of disk instabilities.

Fifty years ago it was popular to consider spiral structure as a wholly magnetic phenomenon. Nowdays, the role of magnetic fields at galactic scales turns out to be of secondary importance. It is reasonable to ask whether magnetic fields can drive star formation and under which conditions the inclusion of strong magnetic fields in early massive protodisks can determine the subsequent evolution of the galaxy as suggested by Totani (1999). He proposes that magnetic fields could be responsible for the origin of the Hubble sequence.

2. GALACTIC MAGNETIC FIELDS AND STAR FORMATION

Observations by Beck & Golla (1988) of far-infrared and radio continuum emission from nearly spiral galaxies suggest that the galactic magnetic field is connected to the current star formation rate. From a statistical analysis of 33 galaxies, Vallée (1994) proposed that the total magnetic field correlates with the star formation rate $B \propto SFR^{0.13}$. One possible explanation explored by Ko & Parker (1989) is that the dynamo action is enhanced by star formation. If this is the case, the existence of a correlation between star formation and magnetic fields should not be interpreted as indicative that fields drive star formation, but just the contrary. Nozakura (1993) argues that there are only small regions of simultaneous occurrence of star formation and dynamo action in the parameter space $[\Sigma_{\rm g}, v_{\rm t}]$.

Another possibility to explain such a correlation is that global star formation is controlled by magnetic fields. However, although magnetic fields seem to control the efficiency of star formation within large clouds (e.g., Beck 1991), the interstellar medium is more strongly influenced by the impact of star formation than by the effects of interstellar magnetic fields. In addition, even if one admits that the collapse of clouds needs fields to transport away angular momentum, there is empirical evidence to suggest that the formation of diffuse clouds is a prerequisite to make the gas dense enough to become opaque (Elmegreen 2002), whereas large-scale instabilities are unable to form cold molecular clouds in an efficient way. In this work, we will assume that the star formation is related to the growth rate of large-scale instabilities. This is an optimistic assumption because even if magnetic fields could promote large-scale instabilities, reducing the potential energy as occurs in the Parker instability, the net nature of magnetic fields is expansive at scales of the diffuse clouds.

3. DISK STAR FORMATION

In our basic formalism, the star formation rate, ϕ, is given by

$$\phi = \epsilon \frac{\Sigma_{\rm g}}{t_{\rm s}}, \qquad (1)$$

where ϵ is the efficiency of star formation and $t_{\rm s}$ is the timescale of star formation. ϵ may not be determined by cloud formation but only by cloud destruction.

From dimensional arguments we get that ϕ may be extremely complex:

$$\phi = \epsilon \Sigma_{\rm g} \Omega \; f(Q, \beta, \beta_{\rm c}, f_{\rm c}, R_{\rm c}/h), \qquad (2)$$

where Ω is the angular velocity, $\beta \equiv \langle B \rangle^2 / (8\pi\rho v_{\rm t}^2)$, with B the total magnetic field, $\beta_{\rm c}$ is the pressure ratio in a typical cloud, $\Sigma_{\rm c}$ and R_c the surface density and cloud radius, $f_{\rm c} = \Sigma_{\rm g}/\Sigma_{\rm c}$, and h the scale height of the disk. The basic assumption is that $t_{\rm s}$ is related to the maximum growth rate of instabilities in the disk in the local linear analysis.

Supercloud formation in sheared magnetic galaxy disks was studied deeply by Elmegreen (1991). It was shown that in normal spiral galaxies only sufficiently small Q will allow fragmentation of wavelets into discrete clouds. In the next, we will see that even when shear is unimportant, the star formation rate is not very sensitive to the strength of the galactic magnetic fields.

4. THE DISPERSION RELATIONSHIP

The starting point is the dimensionless dispersion relation for azimuthal modes in a rotating, infinitely thin gas disk:

$$\omega^4 = A\omega^2 - B, \qquad (3)$$

with

$$A = \frac{k^2}{Q^2}\left(1 + K_{\rm B} + K_{\rm b}\right) - 2\frac{k}{Q^2} + 1 \qquad (4)$$

and

$$B = \frac{k^3}{Q^2} K_{\rm B} \left[k(1 + K_{\rm b}) - 2\right], \qquad (5)$$

where ω is the growth rate in units of κ, k the wavenumber in units of $\pi G \Sigma_{\rm g}/v_{\rm t}^2$ and $K_{\rm B} = v_{\rm A,B}^2/v_{\rm t}^2$, $K_{\rm b} = v_{\rm A,b}^2/v_{\rm t}^2$, with $v_{\rm A,B}$ and $v_{\rm A,b}$ the Alfvèn speeds of the regular and random components of the magnetic field, respectively. The magnetic field used to evaluate $v_{\rm A,b}$ is not necessarily the total random field strength observed in the interstellar medium but only the component that resists the bulk contraction, as measured in the warm component. Instability occurs when $\omega^2 < 0$. The dispersion relationship $\omega^2(k)$ has two branches; we will consider only the low branch in order to select the unstable modes.

We identify $1/t_{\rm s}$ with the maximum growth rate of an unstable mode, $\omega_{\rm max}$, which is given by

$$\omega_{\rm max}^2(Q, K_{\rm B}, K_{\rm b}) \equiv \left| min_k \left[\omega^2(k, Q, K_{\rm B}, K_{\rm b})\right] \right|. \qquad (6)$$

However, it is worthwhile to keep in mind that the condition $\omega^2 < 0$ is not a necessary condition for star formation because there could exist other vias for star formation as that produced in gravitationally unstable compressed shells.

In Fig. 1, $\omega_{\rm max}^2$ versus Q is plotted for different values of $K_{\rm B}$ and $K_{\rm b}$. Not all the space of parameters is physically relevant in this scenario. For the growth rate to be related with star formation it is required that $\omega_{\rm max} \gtrsim \kappa/2$. Otherwise star formation would proceed too slowly. This corresponds to $\log \omega_{\rm max}^2/\kappa^2 \gtrsim -0.6$. In addition, the different curves in Fig. 1 are physically meaningful for k in the range $h < 2\pi/k \lesssim 2$ kpc, i.e. if the disk is only unstable for wavelengths larger than 2 kpc, this instability does not lead to star formation in our model.

In our Galaxy, typical values for the degree of polarization, defined as $P \equiv K_{\rm B}/K_{\rm b}$ ranges 30-50% (Heiles 1995) and it is definitely larger than 10% from observations of the Galactic polarized synchrotron background. Observations of external galaxies also show similar values (Fletcher &

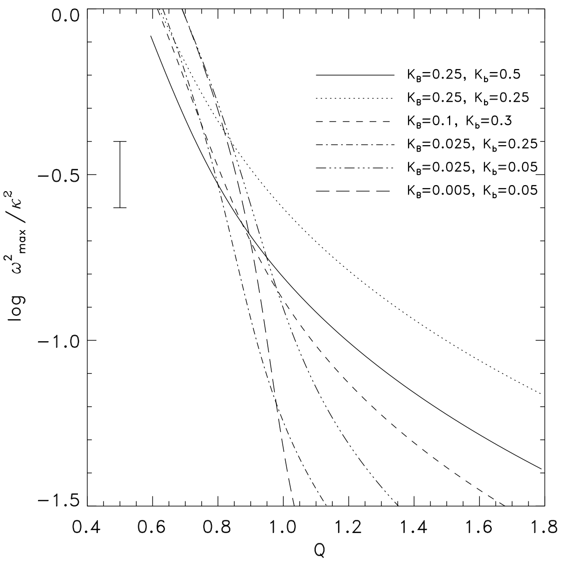

Fig. 1. Growth rate for non-axisymmetric modes in a magnetized rotating gas disk, for different combinations of the parameters $(K_{\rm B}, K_{\rm b})$. In the range of interest (see text) the curves differ by less than 25 percent.

Shukurov 2001, and references therein). The apparent reason is that the large-scale components of the magnetic field in disks are limited by magnetic buoyancy effects, and, in addition, magnetic fields stronger than equipartition values would limit the α–effect. Thus, in Figure 1 we have explored P in the range between 0.1 and 1. The bar on the left indicates variations of 25% in the value of $\omega_{\rm max}$ and corresponds to the maximum variations allow by observations. For the lowest values of both $K_{\rm B}$ and $K_{\rm b}$, magnetic fields are unimportant. Interestingly, magnetic disks are more stable for $Q < 1$ than pure gravitational disks. Except for cases with $P \approx 1$, the growth rate is greatly suppressed for $Q > 1$ compared to the cases with $Q < 0.9$. In the relevant region $Q < 0.9$ the curves lie within the "bar error". This means that if the star formation timescale is proportional to the growth time of large-scale instabilities, the inclusion of magnetic fields is of secondary importance as the small-scale magnetic fields have a stabilizing effect.

For the spiral galaxy NGC 6946, the scale lengths of the magnetic energy density and of cosmic rays are $l_{B^2} = l_{\rm CR} \simeq 8$ kpc, remarkably different to the scale length of the neutral gas $l_\rho = 3.2 \pm 0.1$ kpc (Beck 2002). As a consequence, the dominance of the magnetic field (energy density) increases with galactocentric radius. If magnetic fields drove star formation, it would be difficult to explain the existence of a critical column density threshold for star formation $\Sigma_{\rm c} \sim 0.7 v_{\rm t} \kappa/(3.36G)$, which implies that ambient self-gravity in galaxy disks is required for star formation (e.g., Elmegreen 2002).

5. CONCLUSIONS

For present-day galactic disks, it is thought that the Q-parameter controls star formation even if a large-scale magnetic field is present because when Q is large ($Q > 2$) shear stretches and distorts the forming superclouds before they can collapse. We have shown here than even if shear were unimportant in the central regions of collapsing halos, or though very strong regular magnetic fields were present, the growth rate of unstable modes would not be significantly different (variations < 25%) to expect starbursts induced by strong magnetic fields. On the contrary, magnetic fields give support to the disk. Since Parker instabilities in the disk are not expected to be the dominant mechanism for the formation of clouds, it is difficult to understand under which processes magnetic fields could drive star formation. In this sense, Beck (2002) has argued that the number density of cosmic rays in the interstellar medium depends on the interstellar magnetic fields and the stability of cloud cores is sensitive to the fractional ionization by cosmic rays, but the implications are still unclear. A unified view that combines the empirical laws of star formation (including the nonlinearity of the Schmidt law) and other evidence proposed by Elmegreen (2002) was rooted without invoking the action of galactic magnetic fields. We favour the simplest scenario in which both the star formation and the field strength correlate with gas density, but in which galactic fields cannot drive star formation.

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