MAGNETIC FIELDS IN GALAXIES

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Abstract: Magnetic fields not only provide a basic tool for observing galaxies but constitute an important clue to interpret many dynamic processes taking place in them, mainly in spiral and irregular galaxies. As in the Sun, magnetic fields become important where gravity becomes lower, i.e. in the outermost regions. Any peripheric feature should be explained taking into account magnetic fields, in particular warps, truncations of stellar systems, lopsidedness and so on. Of special cosmological interest is the role of magnetic fields in the rotation curve of spirals. All these questions are still insufficiently explored and the study of magnetic fields in the whole universe open wide areas of interpretation.

Keywords: Magnetic Fields – Galaxies

1 Introduction

The word magnetism has an Indo-European origin, coming from the root “magh” equivalent to “have power”. From the same root are the words “magic” and the spanish “desmayarse” (to faint). In non-scientific forums “magnetism” is still connected to the meaning of “magic” and even with “hypnotic” power to “fascinate”.

When magnetic fields lost their “magic power” to become a physical quantity? As we are aware the first scientific thought about magnetism being applied to a cosmic question was written in the logbook of a well known sailor around 1500:

“Fallo que de Septentrión en Austro, pasando cien leguas de las dichas islas [Azores], que luego en las agujas de marear, que fasta entonces noruesteaban, nordestean una cuarta de viento todo entero... Me puse a tener esto del mundo y fallé que no era redondo en la forma que escriben; salvo que es de la forma de una pera que sea toda muy redonda, salvo all donde tiene el pezón, que allí tiene más alto, o como quien tiene una pelota muy redonda y en un lugar de ella fuese como una teta de mujer allí puesta...". This was written after the third journey to America by Columbus.

There is a recent excellent book in which an exhaustive review of most aspects of galactic magnetism are deeply considered. This is the book "Cosmic Magnetic Fields" edited by Wielebinski and Beck in 2005. This book provides a so extensive and intensive up-to-date of galactic magnetism that it is not noteworthy to repeat hear the most established facts of galactic magnetism. The reader is also addressed to other interesting reviews [1, 2]. We will then concentrate in complementary topics concerning magnetic effects.

In this review we will concentrate in those topics concerning a) large scale magnetic phenomena and b) peripheric ones. This aim is equivalent to deal with controversial and even speculative topics. We will consider also magnetic fields in the pregalactic medium, as a possible clue to many features found today in z=0 galaxies.

For other problems of galactic magnetic fields the reader is addressed to the cited book edited by Wielebinski and Beck. It is nevertheless interesting to briefly list some important topics at lower scale which will be here not considered, in which magnetic fields cannot be ignored or even are dominant, which are at present in phase of study, debate or promising development.

We will not consider the problem of AGN, radio lobes and optical and radio jets even if this is one of the chapters more insufficiently understood of galactic magnetism. Here, fields are not only the clue for explaining the ejection itself and the reacceleration of electrons but can provide an additional mechanism to feed the AGN [4]. The different dynamo mechanisms undoubtedly constitute one of the most important chapters, to explain how a regular field can arise as a consequence of turbulent motions, being a case where we "see" how chaos may produce order. Other small scale phenomena are as well important. Fields play a crutzial role in HI and molecular clouds as well as in the HI diffuse medium, not only as a passive magnitude being amplified, ordered and disordered by them, and not only as a dynamic force, but also as a direct heat productor, via reconnection [5] of magnetic field lines. This could be very important in other lower scale phenomena, such as in HII regions, bubbles and so on, in which the role of reconnection has just begun to be realized. Other phenomena as magnetic fields in bars and spiral arms, reversals and magnetic arms are not the objective here. Magnetic helicity can play an important role in our galaxy as well as in primordial magnetism. Finally, a considerable effort has been made in simulations in magnetized cosmic systems that will be not reviewed here [6, 3]. We will not consider the problem of the tools to observe and measure galactic fields. The synchrotron radiation constitues the most important source of information about magnetic fields, but observing this radiation in some galaxy simply tells us that magnetic fields are there, but obtaining their strength and directions is a more difficult question. The synchrotron brightness not only depends on the magnetic field but also on the number density and energy spectrum of the relativistic electrons. Therefore, some assumptions are needed, for example, equipartition of energies. The polarized synchrotron continuum provides clear information about the direction of the field vector, but only of its component perpendicular to the line-of sight. Faraday rotation also needs an additional observing tool to know the number density of the thermal electrons and we as well need a large number of extragalactic radio sources behind the observed galaxies. In our own Galaxy the number of extragalactic sources and galactic pulsars is high but the existence of a random component of the magnetic fields renders difficult the estimation of the large scale distribution of the regular component. (See Section 6).

2 Why are magnetic fields non-ignorable in any peripheric phenomenon.

The reason by which magnetic fields can be important in peripheric phenomena is double: a) They decrease slowly for increasing radii and b) Order of magnitude arguments show that they are not ignorable. The situation is therefore similar to that in the Sun and magnetic stars. Magnetic fields could compite with gravitation at large radii in normal spiral galaxies and at all radii in dwarf spiral galaxies.

There are evidences for large field strengths in galaxies, even at large radii:

- The field strength of a sample of 74 spiral galaxies is 9 μG [7, 8]. Some galaxies, like M31, M83 and NGC6946 have a strength of the order of 15 μG [8]. Starburst galaxies like M82 reach 50 μG [9]. These are total fields but only the regular fields are able to produce magnetic forces at large-scale. Usually regular and random fields have similar orders, but at large radii the higher degree of polarization, and hence the field regularity, increases. At about 8 kpc the total field of NGC6946 is about 10 μG [8] and the regular field must be slightly lower.

- The magnetic energy density, $B^2/8\pi$ decreases very slowly with radius (Figure 1). For example, in NGC6946 (probably the best observed external galaxy [10]) the radial scale length of the magnetic energy density is very large, of the order of 16 kpc, compared with a radial scale of the density of this galaxy of only 3 kpc. The radial scale length of the regular field is probably larger than 16 kpc, as deduced from the higher degree of polarization at large radii.

- Faraday rotation of extragalactic sources behind M31 lead to magnetic strength similar to those found at lower radii [11].

- In our Galaxy the total field is 6 μG at 10 kpc (about 10 μG in the inner galaxy) [12, 13]. In Figure 2 we reproduce the radial profile [14] for our Galaxy. We

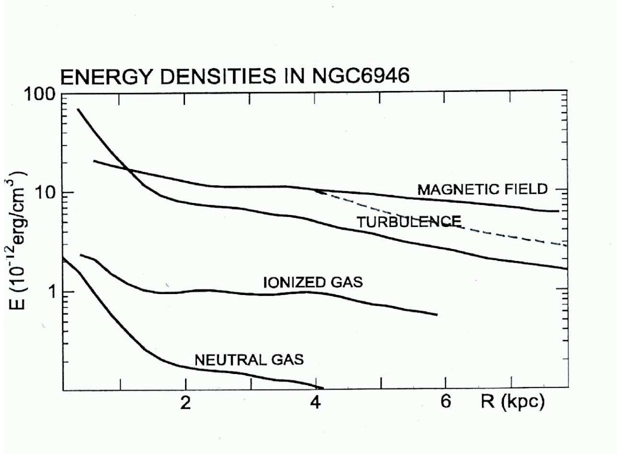

Figure 1: Energy densities in NGC6946 from [14]. The dotted line corresponds to a critical profile. The magnetic force is directed inwards. R is the galactocentric radius along the symmetry plane of the galaxy.

see that at 17 kpc the field strength of the total field is 4 μG. Therefore, the regular field should be only slightly lower.

- The order of magnitude of the strength outside galaxies, in the intra-cluster medium, is similar. Faraday Rotation of sources placed behind the Coma cluster were detected [15] and deduced to be 2 μG [16]; with much higher resolution it was obtained 7-8 μG [17]. Statistically it was deduced a value of 2-12 μG in a sample of 40 galaxies [18, 19, 20]. In addition, μG fields found everywhere, even in extracluster regions near Coma could suggest an equipartition of magnetic and CMB energy densities [21]. In this case, $B^2/8\pi = aT^4$, being T the CMB temperature and a is the radiation pressure constant; $a = 4\sigma/c$ where σ is the Stefan-Boltzmann constant. We should have for a widespread field, $B \approx 3\mu G$. That does nor mean that a cosmological aligned field exists, what would be incompatible with the Cosmological Principle and in desagreement with the absence of a correlation between Rotation Measure in quasars and preferred directions of this relation. It has been estimated 10^{-11}G as an upper limit for such homogeneous aligned cosmological field. However regular fields of the order of few microgauss are normal in clusters and may be present in large filaments and walls of the large scale structure [16]. Then, if the galactic magnetic field must connect with the intracluster field, and given the existence of an active turbulent magnetic diffusion, the regular magnetic field at large radii must be as high as 1-5 μG in normal spiral galaxies .

Field strengths this magnitude cannot be ignored. Or, in other words, if gravitational forces decrease as $1/R^2$ (at large radii, and only due to the visible matter) and magnetic forces decrease much slower, the question is at what R the magnetic force becomes a substantial fraction of the gravitational one. Usually, the criterion for not neglecting a term is when it is at least one tenth of the dominant term. Hence

$$0.1\frac{GM}{R^2}\rho \approx \frac{1}{8\pi}\frac{1}{R^2}\frac{d(R^2B_\varphi^2)}{dR} \tag{1}$$

where M is the visible matter of the galaxy (seen at large radii as producing a central point potential), ρ is the density, B_φ is the azimuthal component of the magnetic field strength (the main component and the one that produces a radial force competing with gravity). For an order of magnitude estimate, and taking into account the above arguments, we assume B_φ independent of R, and consider $\rho = \rho_o e^{-R/R_o}$, then

$$Re^{R/R_o} = \frac{GM\rho_o}{B_\varphi^2} \equiv 4\times 10^4 \frac{M\rho_o}{B_\varphi^2} \tag{2}$$

In the last term of this equation M is measured in $10^{11}M_\odot$, ρ_o in $10^{-23}gcm^{-3}$, B in μG and R in kpc. This transcendent equation would give us the radius at which magnetic fields cannot be ignored when compared with the visible mass of the galaxy.

We now take temptative values, $B_\varphi \approx 5$, $\rho_o \approx 1$, $M \approx 1$, $R_o \approx 3$ and obtain $R \approx 14kpc$. For some galaxies, the influence of magnetic fields can be very important, especially for dwarf spirals, if we take $M = 0.1$, $\rho_o = 0.1$, $B_\varphi = 5$ (as dwarf spirals have even higher strengths [8, 22]) in which magnetic fields should be non-ignorable at all radii.

3 Magnetic fields and rotation curve

The techniques and difficulties for obtaining rotation curves have been detaily reviewed [23]. The possible influence of magnetic fields in the large scale dynamics of a spiral galaxy was early claimed [24, 25]. Later, a substantially different model was presented [26, 27]. In this and a subsequent model it was argued that magnetic fields alone, i.e. without the need of the hypothesis of galactic dark matter, were able to be responsible of the paradoxical large and flat rotation curve of spiral galaxies at the rim. Before reviewing the magnetic hypothesis of the rotation curve, it is salutary to prevent the reader that assuming negligible the contribution of galactic dark matter does not imply at all to assume negligible the amount of cosmological dark matter. On the other hand we cannot disregard the existence of galactic dark matter, but the fact that existing models are able to explain this noticeable rotation curve, must prevent us that trying to explain it, ignoring magnetic fields, can be completely unrealistic. The magnetic hypothesis of the rotation curve is still controversial and a clear example of how much the astronomical community is prone to reject alternative scenarios, even when they are based on classical concepts.

A reconsideration of these magnetic models is now necessary as some of the properties of magnetic fields, such as strengths and radial gradients, which were assumed in these early models, have been recently confirmed by observations.

In a first model [26], it was claimed that fields of the order of 6 μG in the outer parts could provide a centripetal force which together with the gravitational force of visible matter could balance the large centrifugal force. This "large" strength could produce a flaring higher than observed [28]. This important objection prompted us to develop a more detailed model [29]. In this two-dimension model that included horizontal and vertical motions and escape, only fields of $\sim 1\mu G$ at large radii, or slightly lower, were necessary. Today, with the development of measure techniques, it is not necessary to explain why an excessive flaring is not to be expected with fields of order 5 μG, just because this is actually the observed strength. If the hydrostatic equation in the vertical direction leads to an excessive flaring, this just indicates that this equation was not properly applied. It was shown [29] that vertical motions and escape are basic ingredients in the vertical component of the motion equation.

The Virial theorem inform us about the net expansive effect of magnetic fields and however they can produce a centripetal force. No objection can arise from this fact as our model integrated the equation of motion while the Virial theorem is obtained from this equation under some restrictive assumptions. It was shown [29] that this potential incompatibility vanishes when the vertical direction is included. Magnetic fields should have a net expansive effect but they could have a centripetal action in the radial direction compensated with an escape in the vertical one. This second model predicted a vertical escape flux of the order of 0.1 $M_{\odot} yr^{-1}$. Another recent work [30] argued against the hypothesis of magnetically driven rotation also revisiting the Virial theorem. Other arguments in favour or against have been discussed in [31] and will not be repeated here. Rotation curves under the interpretation of dark matter, MOND and magnetic field were analyzed and discussed [32]. These magnetically driven models [26, 29] were presented more than ten years ago. At that time several assumptions were made which have been clearly supported or confirmed by recent observations [31].

Magnetic forces arise from two different effects: the force due to the magnetic pressure gradients and the magnetic tension. The first one, $\nabla(B^2/8\pi)$, is usually centrifugal as B decreases for increasing R. The second one $(1/4\pi)\vec{B} \cdot \nabla\vec{B}$ is, in real galaxies, centripetal. In a pure ionized gas ring, with an azimuthal field, it can be easily demonstrated that this magnetic tension produces an inward force. Then, the direction of the magnetic force arises from the competing action of gradients in the magnetic energy density and the magnetic tension. The most important radial magnetic action, taking into account both effects can be written as a radial force

$$F_{radial} = -\frac{1}{8\pi\rho}\frac{d(R^2 B_\varphi^2)}{dR} \tag{3}$$

There are other forces but this represents the radial force produced by the azimuthal component of the field, which is the most important. We see that when $B_\varphi \propto 1/R$, there is no magnetic force. It is then expected that the B_φ-profile would asymptotically converge to a $B_\varphi \propto 1/R$ profile for very large R, as the force should become vanishing when the density tends to zero. A profile of the type of $B_\varphi \propto 1/R$, or:

$$-\frac{1}{B_\varphi}\frac{dB_\varphi}{dR} = \frac{1}{R} \tag{4}$$

is called the critical profile. When B_φ decreases slowly with R, slowly than the critical profile, then $d/dR(R^2/B_\varphi^2)$ becomes negative and the net force is centripetal. Such a profile is called sub-critical. On the other hand if B_φ decreases faster with R, the net magnetic force is centrifugal and the profile is called super-critical.

In the outer part of real galaxies we could identify three regions: A) An internal one where magnetic fields cannot compite with gravitation and therefore the shape of the B_φ-profile is unimportant, B) An intermediate zone where the B_φ-profile is subcritical and hence the net magnetic force is directed inwards, and C) An outermost region in which the B_φ-profile is critical, or better, asymptotically critical, in which the net magnetic force is null, corresponding to a density tending to zero.

There are at present only two galaxies for which we have data precise enough for this identification. These are NGC6946 and the Milky Way [14]. We reproduce the observational B_φ-profiles for both galaxies together with the critical slope (Figures 1 and 2 from [31]). In NGC6946 the profile is clearly subcritical for $R \geq 3kpc$ indicating a net centripetal force. In the Milky Way we see that the slope is critical for $R \geq 10kpc$, and subcritical for $7 \leq R \leq 10kpc$. For $R < 7kpc$, clearly, magnetic forces should be negligible.

These two plots are in noticeable agreement with the theoretical expectations from the magnetic model and encourage theoreticians and observers to appreciate how magnetic fields should be included in the study of rotation curves, mainly when we see that standard ΛCDM models do not satisfactorily explain them ([33, 34, 35]). Some elliptical galaxies permit the obtention of rotation curves too. As they are gas-poor magnetic fields cannot be important. Rotation curves in these galaxies seem to be keplerian [36, 37].

Other types of galaxies should be investigated for large magnetic dynamical effects:

- Some galaxies exhibit an outer ring (both ellipticals and spirals). An isolated ring should be much more affected by magnetic fields as the force arising from

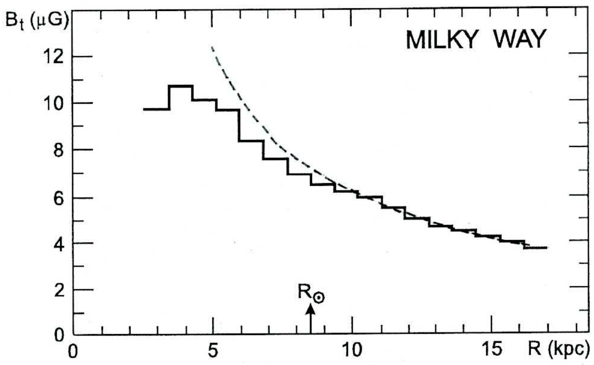

Figure 2: Total magnetic field strength in the Milky Way. A critical profile (dotted line) follows a region with magnetic force directed inwards. From [14] and [31].

the gradient of the magnetic energy density is absent. Therefore, the inwards magnetic force due to the magnetic force should be higher and easier to be identified. We include here polar ring galaxies, whatever was the origin of the ring.

- Dwarf irregular galaxies can be considered extreme late-type spirals. As they are small, according to the Tully-Fisher relation [38] the rotation velocity is low. With a low rotation velocity, dynamo models predict low magnetic fields strengths. However, observations show that these strengths are at least as high as in normal spirals, as above mentioned. Not only the peripheric regions could be influenced by magnetic fields, but the whole irregular galaxy. It should be stressed that magnetic fields also induce large vertical motions and that these galaxies exhibit especially vertical outflows as well as gas and field ejections. A good example is the galaxy DDO 154 [39]. Slowly rotating galaxies of the Local Group reveal strong total magnetic fields of more than 10 μG (in NGC4449 and in IC10) [40].

Other works also present analyses favoring the existence of dynamically non-negligible magnetic fields [36, 41]. For a more complete review the reader is addressed to [32, 31] where arguments in favor and against are analyzed in more detail.

Another complementary problem is the identification of the mechanism producing these fields. The first approach would be how to obtain critical profiles. The possibility of a turbulent magnetic diffusion of the z-component of the magnetic field, amplified and converted into azimuthal field in the central disk by differential rotation to produce critical 1/R-profiles was considered [42, 32, 43, 44]. However the azimuthal component should vanish at z=0 in the galactic plane contrary to the observations [44, 45]. See, however [11]. Other dynamo-like mechanisms are able to produce critical profiles [32].

4 Truncations of stellar disks.

Truncations of stellar disks were discovered and studied by van der Kruit and Searle [46, 47, 48, 49]. Other more recent observations have been reported in [50, 51] and many others. We understand that "truncations" should be "complete". With the word "complete" we understand that beyond a certain radius, R_{max}, the density of the stellar system is null (within observational limits). This was the first description proposed by van der Kruit and Searle and this interpretation was followed and adopted by most astronomers [52, 53]. Clearly, truncations cannot be completely sharp, only relatively sharp [54]. Therefore, we can speak of a truncation curve , $T(R)$, defined as the difference between the observed light profile and the extrapolated exponential of the inner untruncated disk. Clearly, when we are observing edge-on galaxies what we observe is the surface brightness but the deprojected surface brightness should be proportional to the density of stars. We understand that truncations are peripheric, complete and not completely sharp.

From the observational point of view, several recent papers [55, 56, 57, 58, 59], have found that the "truncation" is not a good description of the phenomenon. They find that the correct description is a double exponential profile with a break in between. Sometimes, the second exponential is steeper, sometimes it is shallower and sometimes the profile is unbroken. This simple scheme proposed in [55] has been enriched in more recent papers where the authors divide these three types into a series of subtypes, often introducing a third exponential which can be either shallower or steeper than the second, rendering the initial classification more complex. When the second exponential is shallower they also use the word "untitruncation". Most of their analysis is based in face-on spirals and in the optical, but edge-on galaxies also in the optical have also been studied [59].

A description more in agreement with the early interpretation of van der Kruit and Searle and Binney and Tremaine has been observed [60, 61, 62]. Following these authors there is a real non-sharp complete truncation being the truncation curve given by a fitting formula proportional to $(R_{max} - R)^{-\alpha}$ where α is close to unity. Figure 3 shows a typical truncation profile and in Figure 4 we plot the truncation curve. As these authors work in the NIR and the formers in the optical, the first explanation would be that both wavelengths, tracing different populations, are intrinsically different. However, the galaxy NGC6504 was observed in the optical and in the NIR [63] with the best depth available and it was found that the optical profile is as well

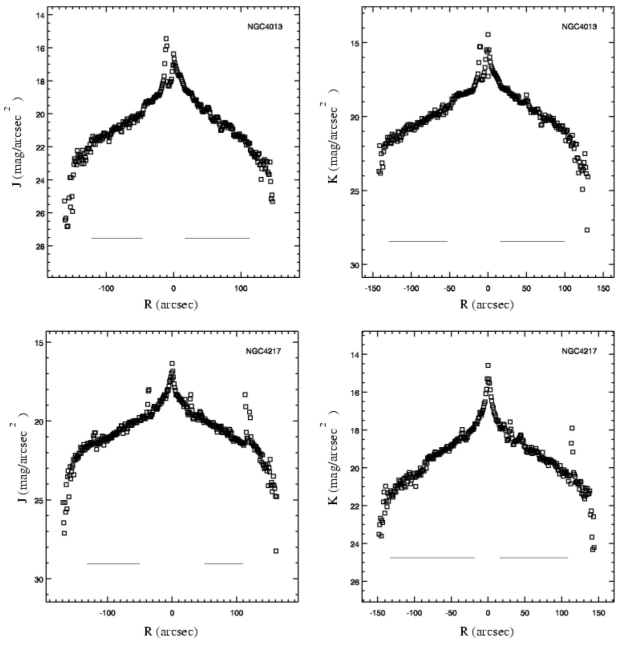

Figure 3: Truncation profile in the spiral galaxy NGC4013 and NGC4217 ([60]).

really truncated. They have reached 28.5 magnitudes per arcsec square with no trace of stars beyond $R_{max} = 82$ arcsec. Profiles in the optical and in the NIR have a slope continuously steeping without evidence of a double exponential. (See Figure 5).

The NIR profiles also confirm the existence of antitruncations such as that of NGC2654 [62] as shown in Figure 6.

We are here, however, more interested in the physical process responsible of truncations. This section is included in this review because magnetism is one of the proposed mechanisms [64]. The scenario is simple and connected with that of magnetically driven rotation (see last section). Suppose gas moving in circular orbits with gravity plus magnetic fields in balance with the centrifugal force. Suddenly (in a very short time compared with typical dynamic times) some stars are born from this rotating gas. Magnetic fields can no longer act on the stars. Therefore new born

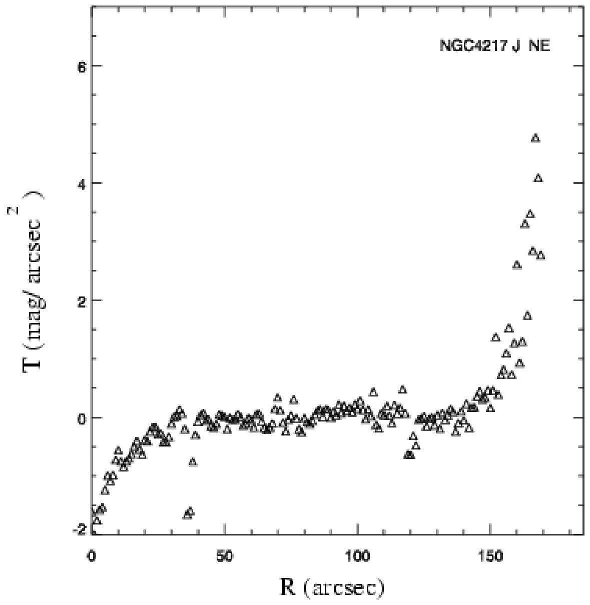

Figure 4: Truncation curve in the spiral galaxy NGC4217 ([60]).

stars are formed out of equilibrium of forces. Then, some stars migrate to larger radii orbits (producing antitruncations) and others escape from the galaxy in the radial direction (producing truncations).

This hypothesis has the "a priori" advantage that, qualitatively at least, is able to explain both antitruncations and truncations. For the case of truncations, we deduced [64] by means of our simpler model that

$$R_{max} = \frac{2GM}{\theta_o^2} \tag{5}$$

being M the visible mass of the galaxy and θ_o the asymptotic rotation velocity ($\theta_o = \theta\,(R \rightarrow \infty)$). Taking into account the Tully-Fisher relation $L \propto \theta_o^x$, where x is typically 3.5, we obtain either $R_{max} \propto \theta_o^{1.5}$ or $R_{max} \propto L^{0.7}$. The relation between R_{max} and $\theta_o^{1.5}$ is fully confirmed by observations. (See Figure 7 and [54] for edge-on galaxies). We also see that truncations should be more difficult to be detected in large galaxies, as R_{max} is higher. This is also confirmed by the observations.

There are other non-magnetic models for the explanation of truncations. If we assume that the initial gaseous disk was exponential without neither truncations nor

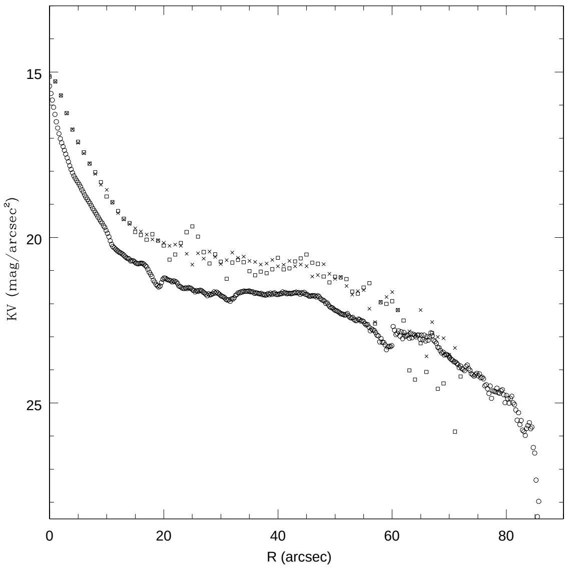

Figure 5: Truncation curves in the spiral galaxy NGC6504 in the optical and NIR ([63]).

breaks, and if the density of stars drop beyond an R_{max}, either, for some reason, the gas beyond R_{max} has no ability to form stars, or the stars once formed flow away. Below a density threshold, stars could be no longer formed out of gas. The threshold hypothesis [65, 66] is of the former type. The excess of angular momentum induced by a large differential rotation beyond R_{max}, could cause the inability to form stars too [67] . This explanation would also be of the former type. Clearly, magnetically driven truncations belong to the second type of explanations.

There is an interesting argument [68] against the scenarios inhibiting star formation. A sudden drop in the rotation curve takes place at R_{max}. This drop was also found in NGC5055 [69].

This drop indicates that there is a rather sharp decrease in the total mass (gas plus stars) not only of stars. Another argument favoring models which do involve large scale dynamics, is that the radial decrease of gas amount is due to a radial decrease in the number of molecular clouds, but the density in these outer clouds is not different when compared with the inner clouds.

Another interesting model, also involving large scale motions, has been proposed

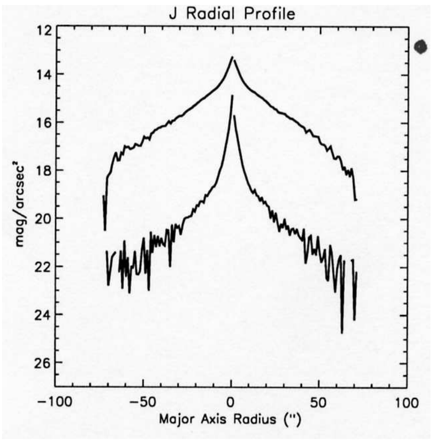

Figure 6: Antitruncation in the NIR (J band) in the galaxy NGC684.

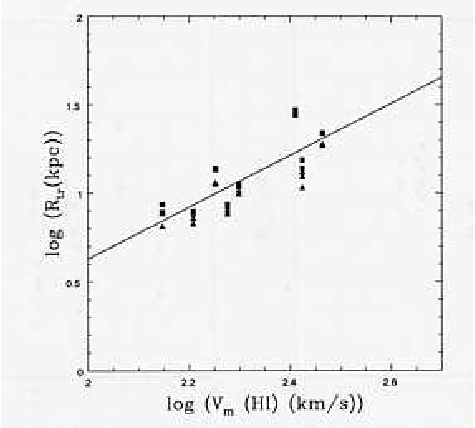

Figure 7: Relation between the truncation radius and the asymptotic velocity.

[68, 54], in which the disk was formed in two steps. In the first step the inner disk was formed with a size R_{max}. This finite size R_{max} was established by the maximum specific angular momentum. The extragalactic gas falling later, in the second step, produced the outer region.

With respect this model defended in [54] with the first settled truncated rigid disc and a warped external disc in a more recent step, relating R_{max} and the radius at which the warp begins, we should have two comments: First, optical warps exist and even most galaxies have warped stellar systems [70, 71, 72]. Second, very early z=1 galaxies show optical warps and much larger than the present one [98].

An important observational fact is that R_{max} increases with the band wavelength used (see for instance Figure 7). This is another reason to use NIR to detect truncations. This is also a constraint that models must explain. It is interesting to note that breaks are also observed in large-z galaxies [74, 58].

5 Warps.

It is well known that most spiral galaxies have a warped plane when observed at 21 cm ([75, 76, 77] and others). The warps are also observed in the optical ([70, 72, 60, 71, 79]). The frequency of warped disk in spiral galaxies is very large. In contrast, no lenticular galaxy has been observed to be warped [72]. All the spiral galaxies with very extended HI-disk are warped. These facts suggest that the mechanism producing the bending acts directly on the gas and that the stellar warp is the consequence of being stars born in a warped disk. Therefore, we have searched for a magnetic scenario being in this case the extragalactic magnetic fields responsible of the warps.

There are other hypothesis (see [80, 81, 68], for instance). Tidal interaction [82] may explain some warps but not their high frequency: Near all spiral galaxies are warped. Sparke and Casertano [95] showed that some discrete modes can survive, but they did not take into account the reaction of the halo, what would destroy the warp in few orbit periods. Binney [80] considered the interesting possibility that the permanent accretion of material into the DM halo would produce a continuous redistribution of its angular momentum and the warps would be created by the reaction of the disk to this redistribution.

It seems that warping could be a natural response of the outer disk to a series of stimulations and that different mechanisms could be responsible in different galaxies. However the observation of large edge-on spiral galaxies could contribute to determine the dominant scenario. The intergalactic medium could play an important role [83] by interaction with extragalactic clouds [84, 85], by the flowing of galaxies in an intra-cluster medium [86] or by extragalactic magnetic fields [87].

The magnetic model of warps is an interesting possibility. It is known that a warp will disappear in a time of about 2 Gyr [80], or even shorter in the magnetic case. However, in the magnetic model of warps, the field configuration is not an initial condition but extragalactic fields are acting permanently. Any cause of warps must act permanently.

The intergalactic magnetic field must penetrate in the outer disk by some mechanism at work in the external region. Probably the intercharge of matter and fields between disk and intracluster medium is very active as vertical out and inflows are very common, transporting these flows the frozen-in field lines. This intercharge can be very active mainly in the outer disk where the low surface density produces low gravitation enabling vertical motions. These flows could be considered as turbulent (even if they are not properly turbulent) and the mechanism of field transport could then be treated as a turbulent magnetic diffusion. The coefficient of turbulent magnetic diffusion, $\beta = (B'/B)v'l$, should not be constant but highly radial dependent. B' and B are the fluctuating and mean magnetic field strengths, v' a characteristic velocity of the fluctuations and l a typical eddy size (e.g. [88]). We take $B'/B \sim 1/3$, as the random component is slightly lower than the regular one [8] and $l \approx 1$ kpc is the size of the larger eddies, that can be identified with the thickness of the disk. It is difficult to assess values for v' but it must change very much with radius. Taking $v' \sim 1$ km/s in the inner disk we obtain β (inner) $= 10^{26}$ cm^{2}s^{-1}, which is even larger than currently adopted values [89, 90, 91].

The turbulent process producing the turbulent diffusion of magnetic fields is usually assumed to consist in bubbles arising massive type II supernovae which reach typical velocities of about 100 km/s and heigths around 1 kpc from the plane, usually raining back [92]. Observation of bubbles, holes or chimneys are more frequent in spiral arms, with a higher star formation rate. Their effects are more importat at large galactocentric radii with a lower vertical component of gravity. With these high values of v' we would obtain β (outer) larger than $= 10^{28}$ cm^{2}s^{-1} [93] following recent developments of the fountain model.

The diffusion time $\tau = l^2/\beta$ becomes τ (inner) $\approx 3 \times 10^9$ years and τ (outer) $\approx 3 \times 10^7$ years. The first one is larger than the rotation time, then the extragalactic B_r field could not effectively penetrate in the inner disk, but B_r should have the same extragalactic value in the warped region. Therefore, radial component of the vertical field gradient should very effective in producing warps.

The magnetic model was designed to explain S-warps (m=1) which is the most frequent type (68% in the large sample of 325 edge-on galaxies [79]). This model barely explain m=0 warps (U-shaped profile); they should be interpreted as arising from gradients in the extragalactic field, with characteristic length of the order of the galaxy size. The generation of asymmetric warps by other mechanisms have been considered [94, 84].

There seems to be a common orientation of warps in relative low-scale clusters. For example it was noticed [96] that in the Local Group the warps of the Milky Way, M31 and M33 show a very noticeable alignment. Also a common orientation of warps in the neighborhood of the Milky Way was found [87, 97]. This fact suggests an extragalactic origin.

It is interesting to notice too that warps are observed in high redshift galaxies [98]. The warps are even larger in these first steps in galaxy evolution. If warps are driven by extragalactic magnetic fields this fact would be interpreted as a result of past higher magnetic strengths. It should be taken into account that due to expansion

Ba^2= constant, being a the cosmological scale factor, $a^{-1} = z+1$, therefore at $z \sim 1$, in the Hubble Deep Field, the magnetic strengths were 4 times higher than today.

Intergalactic magnetic fields may produce warps, being the angle of 45^o between the rotation axis and the direction of the field, the angle of higher efficiency for bending the disk. When both directions are closer, a larger flaring of the disc would be expected. When the field direction lies close to the galactic plane it would produce lopsidedness, i.e. elliptical shapes in the outer isophotes with radial increase of eccentricity [99]. This could provide a basis of interpretation of observed lopsidedness ([100, 101, 102, 103]). In particular, it was found [101] found that about 50% of spiral galaxies exhibit lopsidedness and that about 20% of the galaxies have a lopsidedness magnitude $< A_1/A_o > \geq 0.19$ [102] . Also the lopsidedness of the young stellar population is greater than the old one [104]. This indicates that the gas is the first component suffering the distortion. An extragalactic magnetic field is therefore a temptative explanation of lopsidedness that should be explored.

6 Galactic magnetic fields.

A very promising field is the interpretation of the CMB taking into account primordial pre-recombination magnetic fields and even the possibility of finding observational traces of their existence with the great sensitivity of the space mission Planck. There is a wide Planck team interested on this topic [107]. A knowledge of primordial magnetic fields provides an understanding of their influence in galaxy birth and evolution.

Observations of CMB can not only provide information about the magnetized pregalactic medium. They also constitute the most complete direct information of the large scale magnetic field of the Milky Way and some other nearby galaxies. From the all-sky maps obtained at different wavelengths we may obtain the maps of the polarized synchrotron continuum emission and hence very important restrictions on the 3D-distribution of the galactic field.

Preliminary calculations can be obtained using WMAP data. The procedure is as follows: We can select different models proposed in the literature with different free parameters. We them obtain for each model and for each set of parameters of each model the best fit to the real data. We have considered five models and about 70000 sets of parameters per model. In Figure 8 we plot the polarization angle obtained at 22 GHz by WMAP and in Figure 9 the best fir model with the best set of parameters. The model coincides with that proposed in [108] even if different parameters better reproduce the observational map. Nevertheless, this type of approach does not permit the firm withdrawal of other models and we will must wait for Planck, with its much higher sensitivity for polarization to determine the 3D distribution of magnetic fields in our galaxy.

Other techniques [109, 110] to determine the large scale configuration of the

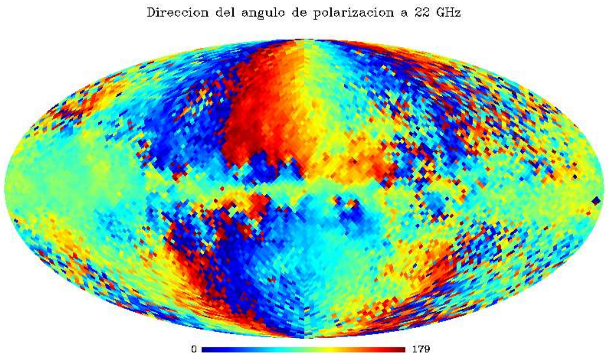

Figure 8: All sky polarization angle from WMAP at 22 GHz.

galactic magnetic field are based on Faraday Rotation of pulsars and extragalactic radio sources. Pulsars inform about the field near the plane and have the advantage of a null intrinsic Faraday Rotation. These techniques do not provide a common picture yet. Probably, the magnetic field of the Milky Way has an "axisymmetric spiral" distribution, distorted by spiral arms and random fluctuations.

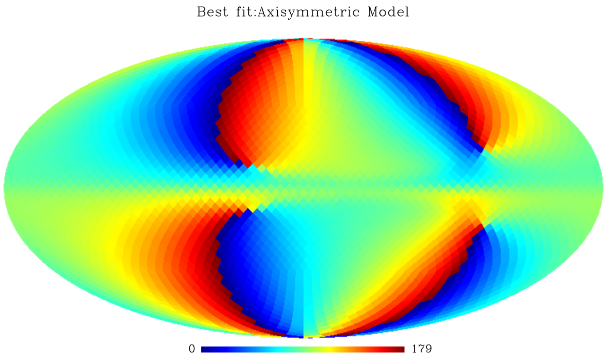

Figure 9: Best fit model of the all sky polarization angle.

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