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MAGNETIC FIELDS AND STAR FORMATION IN SPIRAL GALAXIES

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RESUMEN

Se hace una reseña de los principales resultados de observaciones de radio-contínuo y polarización acerca de la magnitud y patrón a gran escala de los campos magnéticos en galaxias tanto de canto como de cara, y se hace una comparación con una muestra de galaxias con diferentes tipos morfológicos, inclinaciones, y tasas de formación estelar (SFRs por sus siglas en inglés). Encontramos que galaxias con baja SFR tienen mayores fracciones térmicas/menores fracciones sincrotrón que aquellas con SFRs normales o altas. Adoptando un modelo de equipartición, concluimos que la emisión no térmica y el *campo magnético total* crecen linealmente con la SFR, mientras que la *intensidad* del campo magnético *regular* no parece depender de ésta.

Estudiamos también la estructura y ancho de los discos en galaxias con altas inclinaciones (de canto). Encontramos que en cuatro galaxias –a pesar de su diferente aspecto en el radio– la escala vertical para ambos, el disco delgado y el disco ancho/halo, son aproximadamente iguales (0.3/1.8 kpc a 4.75 GHz), independientemente de su diferente SFR. Esto implica que todas estas galaxias producen un viento galáctico, en el cual la velocidad de flujo de los rayos cósmicos se encuentra determinada por la magnitud del campo magnético total dentro del disco. Las galaxias en nuestra muestra muestran también una configuración del campo magnético a grandes escalas similar, paralela cerca del plano medio galáctico y con forma de X lejos de éste, independientemente del tipo de Hubble y la SFR en el disco. Concluimos así que también patrón del campo magnético a *grandes escalas* no depende de la SFR.

ABSTRACT

The main observational results from radio continuum and polarization observations about the magnetic field strength and large-scale pattern for face-on and edge-on spiral galaxies are summarized and compared within our sample of galaxies of different morphological types, inclinations, and star formation rates (SFR). We found that galaxies with low SFR have higher thermal fractions/smaller synchrotron fractions than those with normal or high SFR. Adopting an equipartition model, we conclude that the nonthermal radio emission and the *total magnetic field* strength grow nonlinearly with SFR, while the *regular* magnetic field *strength* does not seem to depend on SFR.

We also studied the magnetic field structure and disk thicknesses in highly inclined (edge-on) galaxies. We found in four galaxies that –despite their different radio appearance– the vertical scale heights for both, the thin and thick disk/halo, are about equal (0.3/1.8 kpc at 4.75 GHz), independently of their different SFR. This implies that all these galaxies host a galactic wind, in which the bulk velocity of the cosmic rays (CR) is determined by the total field strength within the galactic disk. The galaxies in our sample also show a similar large-scale magnetic field configuration, parallel to the midplane and X-shaped further away from the disk plane, independent of Hubble type and SFR in the disk. Hence we conclude that also the *large-scale* magnetic field *pattern* does not depend on the amount of SFR.

Key Words: galaxies: halos — galaxies: individual (NGC 891, NGC 4631) — galaxies: magnetic fields — galaxies: spiral — polarization

1. INTRODUCTION

Radio observations of the continuum emission in the cm-wavelength regime are the best way to study magnetic fields in galaxies. The total intensity of the synchrotron emission gives the strength of the total magnetic field. The linearly polarized intensity reveals the strength and the structure of the resolved regular field in the sky plane (i.e. perpendicular to the line of sight). However, the observed polarization vectors suffer Faraday rotation and depolarization on their way from the radiation's origin to us. Correction for Faraday rotation is possible with observations at two –or better more– wavelengths by determining the rotation measure RM (being proportional to $\int n_e B_\parallel dl$). $B_\parallel$ is the coherent magnetic

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field parallel to the line of sight, and its sign gives the direction of this magnetic field component. Both field components, parallel and perpendicular to the line of sight, enable us in principle to deduce a 3-dimensional picture of the large-scale magnetic field. Note, however, that the polarized intensity is only sensitive to the field orientation, i.e. it does not distinguish between parallel and antiparallel field directions in the plane of the sky, whereas the RM is large for parallel fields along the line of sight, but zero for parallel and antiparallel fields (of equal strength). Magnetic fields consist of regular and turbulent components. The total magnetic field strength in a galaxy can be estimated from the nonthermal radio emission under the assumption of equipartition between the energies of the magnetic field and the relativistic particles (the so-called *energy equipartition*) as described in Beck & Krause (2005).

2. OBSERVATIONAL RESULTS OF MAGNETIC FIELDS

2.1. *Spiral Galaxies seen face-on*

The mean equipartition value for the total magnetic field strength for a sample of 74 spiral galaxies observed by Niklas (1995) is on average $9 \pm 3\,\mu$G. It can, however, reach locally higher values *within* the spiral arms of up to $20\,\mu$G. Strongly interacting galaxies or galaxies with a high star formation rate tend to have generally stronger total magnetic fields. The strength of the regular magnetic fields in spiral galaxies (observed with a spatial resolution of a few 100pc) are typically 1–5 μG, and may reach locally values up to $10 - 15\ \mu$G as e.g. in NGC 6946 (Beck 2008) and M51 (Fletcher et al. 2008).

The turbulent magnetic field is typically strongest along the optical spiral arms, whereas the regular fields are strongest in between the optical spiral arms, or at the inner edge of the density-wave spiral arm. Sometimes, the interarmed region is filled smoothly with regular fields, in other cases the large-scale field form long filaments of polarized intensity like in IC342 (Krause et al. 1989; Krause 1993) or so-called *magnetic spiral arms* like in NGC 6946 (Beck & Hoernes 1996).

The magnetic lines of the large-scale field form generally a spiral pattern with pitch-angles from 10° to 40° which are similar to the pitch angles of the optical spiral arms. Further, spiral magnetic fields have even been observed in flocculent and irregular galaxies.

2.2. *Spiral Galaxies seen edge-on*

Several edge-on galaxies of different Hubble type and covering a wide range in SFR were observed with high sensitivity in radio continuum and linear polarization. These observations show that the magnetic field structure is mainly *parallel to the disk* along the midplane of the disk (with the only exception of NGC 4631) as expected from observations of face-on galaxies and their magnetic field amplification by the action of a mean-field $\alpha\Omega$-dynamo (e.g. Beck et al. 1996). Away from the disk the magnetic field has also vertical components increasing with distance from the disk and with radius (Krause 2004; Soida 2005; Krause et al. 2006; Heesen et al. 2008b). Hence, the large-scale magnetic field looks X-shaped away from the plane. As an example, we show the magnetic field vectors of the edge-on galaxy NGC 891 together with the radio continuum emission at λ3.6cm (made with the Effelsberg 100 m telescope[2] overlayed on an optical image of the galaxy in Figure 1.

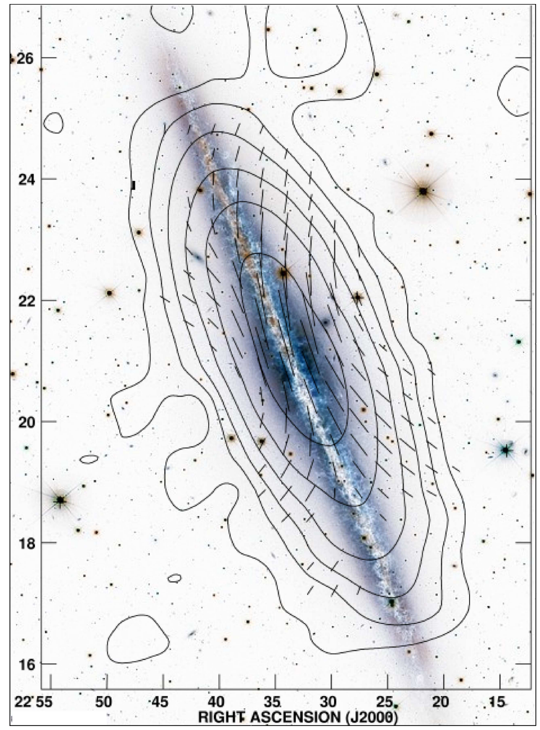

Fig. 1. Radio continuum emission of the edge-on spiral galaxy NGC 891 at λ3.6cm (8.35 GHz) with the 100 m Effelsberg telescope with a resolution of 84″ $HPBW$. The contours give the total intensities, the vectors the intrinsic magnetic field orientation (Copyright: MPIfR Bonn). The radio map is overlayed on an optical image of NGC 891 from the Canada-France-Hawaii Telescope/(c)1999 CFHT/Coelum.

[2]The Effelsberg 100 m is operated by Max-Planck-Institut für Radioastronomie (MPIfR) in Bonn.

The rotation measures (RM) determined between our λ3.6cm-map and the λ6.2cm-map of Sukumar & Allen (1991) vary smoothly along the major axis of the galaxy with positive values in the southern part and negative in the northern part of the galaxy. This indicates a large-scale toroidal field within the galactic disk. As the RMs have equal signs above and below the disk along the major axis, the azimuthal magnetic field in NGC 891 seems to be an *even* axisymmetric spiral field (ASS) (Krause 1990) as generated by a mean-field $\alpha\Omega-$ dynamo (cf. § 4).

From the HI- and CO-line observations (Rupen 1991; García-Burillo & Guélin 1995) we know that the rotation velocities in NGC 891 are also negative in the northern part of the galaxy and positive in the southern one. Assuming trailing optical spiral arms (and a magnetic field *orientation* primarily parallel to the opical arms as observed in face-on galaxies) we can infer that the *direction* of the large-scale ASS field in NGC 891 is *outwards.* Together with NGC 4254 (Chyży 2008) and NGC 5775 (Soida et al. in prep.) these are the first examples of outwards directed ASS fields. The other four galaxies for which the direction of the ASS could be determined up to now (M31, IC342, NGC 253, and NGC 6949) were all inwards directed, which could not be explained up to now (Krause & Beck 1998). The three counterexamples NGC 891, NGC 4254, and NGC 5775 balances the statistics.

3. TOTAL MAGNETIC FIELD STRENGTH AND STAR FORMATION

Observations of a sample of three late-type galaxies with low surface-brightness and the radio-weak edge-on galaxy NGC 5907 (all with a low SFR) revealed that they all have an unusually high thermal fraction and weak total and regular magnetic fields (Chyży 2007; Dumke et al. 2000). However, these objects still follow the total radio-FIR correlation, extending it to the lowest values measured so far. Hence, these galaxies have a lower fraction of synchrotron emission than galaxies with higher SFR. It is already known that the thermal intensity is proportional to the SFR. Our findings fits to the equipartition model for the radio-FIR correlation (Niklas & Beck 1997), according to which the nonthermal emission increases $\propto SFR^{\approx 1.4}$ and the *total* magnetic field strength as well as the ratio of nonthermal-to-thermal emission increases with $\propto SFR^{\approx 0.4}$.

We also determined the exponential scale heights of the total power emission at λ6 cm for four edge-on galaxies (NGC 253, NGC 891, NGC 3628,

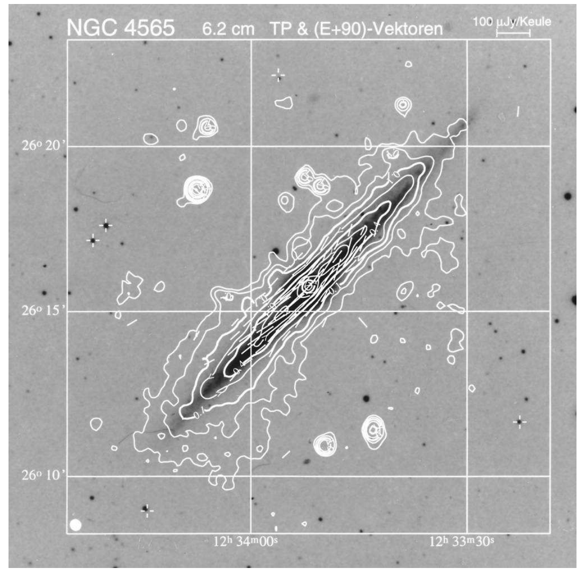

Fig. 2. Radio continuum emission of the edge-on spiral galaxy NGC 4565 at λ6.2cm (4.85 GHz), combined from observations with the VLA and the 100 m Effelsberg telescope with 20″ *HPBW* (Dumke 1997). The contours give the total intensities, the vectors the intrinsic magnetic field orientation. The radio map is overlayed on an optical image of NGC 4565 (Copyright: MPIfR Bonn).

NGC 4565) for which we have combined interferometer and single-dish data (VLA and the 100 m Effelsberg) at this wavelength. The map of NGC 4565 is shown in Figure 2. In spite of their different intensities and extents of the radio emission, the *scale heights* of the thin disk and the thick disk/halo are similar in this sample (300pc and 1.8kpc) (Dumke & Krause 1998; Heesen et al. 2008). We stress that our sample includes the brightest halo observed so far, NGC 253, with a very high SFR as well as one of the weakest halos, NGC 4565, with a small SFR.

In the case of NGC 253, Heesen et al. (2008a) found that the local scaleheights of the radio emission are linear functions of the cosmic ray electron (CRE) synchrotron lifetimes in the underlying disk. This implies that the cosmic ray transport is mainly in vertical direction with a cosmic ray bulk speed (determined as the ratio of the total power scaleheight and the CRE synchrotron lifetimes) of at least 280 km/s. The cosmic ray bulk speed can be best described as a convective transport of cosmic rays (CR) in a galactic wind (as proposed e.g. by Breitschwerdt et al. 1991), and the above deduced correlations give observational support for the existence of such a galactic wind.

The fact that we observe similar averaged scaleheights at λ6 cm for the four galaxies mentioned above imply –together with the assumption that the synchrotron lifetimes ($\propto$ B^{-2}) determine the disk thicknesses– that the CR bulk speed (or galactic wind velocity) is proportional to B^2, and hence proportional to SFR$^{0.8}$.

4. REGULAR MAGNETIC FIELD AND STAR FORMATION

The polarized intensity in spiral galaxies allows to estimate the regular magnetic field strength and the observed degree of polarization P (as determined by the ratio of polarized intensity and total intensity) is a measure of the degree of uniformity of the magnetic field. As discussed in § 3 the low brightness edge-on galaxy NGC 5907 has a weak total and polarized intensity, a high thermal fraction and a low SFR. On the other hand, NGC 891 (see Figure 1) has strong total and polarized intensities, a normal thermal fraction and strong star formation. Surprisingly, the degree of polarization at λ6 cm at a resolution of 84$''$ $HPBW$ (half power beam width) is equal in both galaxies, P = 3.2%. When we average the Stokes I-, U-, and Q-maps over the total galaxy (as described in Stil et al. 2008), the global degree of polarization in NGC 5907 is P = 2.2%, whereas in NGC 891 it is only P = 1.6%.

Similarly, we integrated the polarization properties in 41 nearby spiral galaxies and found that (independently of inclination effects) the degree of polarization is lower ($<$ 4%) for more luminous galaxies, in particular those for $L_{4.8} > 2 \times 10^{21}$ WHz^{-1} (Stil et al. 2008). The brightest galaxies are those with the highest SFR. Of course, the mean-field dynamo needs star formation and supernova remnants as the driving force for velocities in vertical direction. From our observations, however, we conclude that stronger star formation seems to reduce the magnetic field regularity.

On kpc-scales, Chyży (2008) analyzed the correlation between magnetic field regularity and SFR locally within one galaxy, NGC 4254. While he found a strong correlation between the total field strength and the local SFR, he found an anticorrelation of magnetic field regularity with SFR and could not detect any correlation between the regular field strength and the local SFR.

In our sample of 11 observed edge-on galaxies we found in all of them with one exception (in the inner part of NGC 4631) mainly a disk-parallel magnetic field together with the X-shaped poloidal field in the halo. Our sample includes spiral galaxies of very different Hubble type and SFR, ranging from 0.5 $\leq$ SFR $\leq$ 27. The disk-parallel magnetic field along the galactic disk is the expected edge-on projection of the spiral-field within the disk as observed in face-on galaxies. It is generally thought to be generated by a mean-field $\alpha\Omega-$ dynamo for which the most easily excited field pattern is the axismmetric spiral (ASS) field (e.g. Ruzmaikin et al. 1988). The dynamo acts most effectively in regions of strong differential rotation in the disk. NGC 4631, however, which has a disk-parallel magnetic field along the disk only at radii $\geq$ 5kpc, shows for smaller radii a vertical large-scale field also in the midplane of the disk, as visible in Figure 3. The inner $\approx$ 5 kpc (140$''$) is just the region of NGC 4631 where the rotation curve rises nearly rigidly (Golla & Wielebinski 1994), hence the mean-field $\alpha\Omega-$ dynamo may not work effectively in this inner part of NGC 4631 and hence may not amplify a disk-parallel large-scale field.

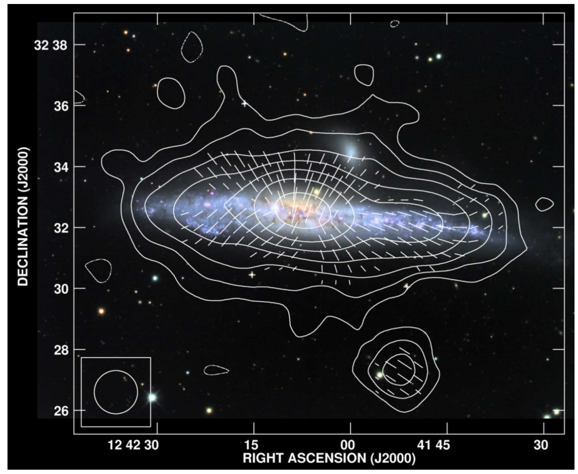

Fig. 3. Radio continuum emission of the edge-on spiral galaxy NGC 4631 at λ3.6cm (8.35 GHz) with the 100 m Effelsberg telescope with 84$''$ $HPBW$. The contours in give the total intensities, the vectors the intrinsic magnetic field orientation. The radio map is overlayed on an optical image of NGC 4631 taken with the Misti Mountain Observatory (Copyright: MPIfR Bonn).

The even ASS magnetic disk field (as discussed in § 2.2) is –according to the mean-field dynamo theory– accompanied with a quadrupolar poloidal field, which is, however, a factor of about 10 weaker than the toroidal disk field. This means that the poloidal part of the ASS dynamo mode alone cannot explain the observed X-shaped structures in edge-on galaxies as the field strengths there seems to be comparable to the large-scale disk field strengths. Model calculations of the mean-field $\alpha\Omega$-dynamo for a disk surrounded by a spherical halo including a *galactic wind* (Brandenburg et al. 1993) simulated similar field configurations as the observed ones. Such a galactic wind (which has already been observationally deduced e.g. as described in § 3) can also solve the helicity problem of dynamo action (e.g. Sur et al. 2007). Recent numerical dynamo simulations indicate a self-generation of vertical gas velocities (D. Elstner, priv. comm.).

As a summary, we conclude that –though a high SFR in the disk increases the total magnetic field in the disk and halo– it cannot change the global field configuration nor influences the global scale heights of the radio emission. The similar scale heights and magnetic field configurations in these galaxies imly that the total magnetic field strength regulates the galactic wind velocities.

REFERENCES

Beck, R. 2008, A&A, 470, 539
Beck, R., Brandenburg, A., Moss, D., Shukurov, A., & Sokoloff, D. 1996, ARA&A, 34, 155
Beck, R., & Hoernes, P. 1996, Nature, 379, 47
Beck, R., & Krause, M. 2005, Astron. Nachr., 326, 414
Brandenburg, A., Donner, K. J., Moss, D., Shukurov, A., Sokoloff, D. D., & Tuominen, I. 1993, A&A, 271, 36
Breitschwerdt, D., McKenzie, J. F., & Völk, H. J. 1991, A&A, 245, 79
Chyży, K. T. 2008, A&A, 482, 755
Chyży, K. T., Bomans, D. J., Krause, M., Beck, R., Soida, M., & Urbanik, M. 2007, A&A, 462, 933
Dumke, M. 1997, PhD thesis, University of Bonn
Dumke, M., & Krause, M. 1998, Lect. Notes Phys., 506, 555
Dumke, M., Krause, M., & Wielebinski, R., 2000, A&A, 355, 512
Fletcher, A., Beck, R., Berkhuijsen, E. M., Horellou, C., & Shukurov, A. 2008, A&A, submitted
García-Burillo, S., & Guélin, M. 1995, A&A, 299, 657
Golla, G., & Wielebinski, R. 1994, A&A, 286, 733
Heesen, V., Beck, R., Krause, M., & Dettmar, R.-J. 2008a, A&A, submitted
Heesen, V., Krause, M., Beck, R., Dettmar, R.-J., & Ehle, M. 2008b, A&A, submitted
Krause, M. 1990, in IAU Symp. 140, Galactic and intergalactic magnetic fields, ed. R. Beck, R. Wielebinski, & P.P. Kronberg (Dordrecht: Kluwer), 187
__________. 1993, in IAU Symp. 157, The Cosmic Dynamo, ed. F. Krause, K.H. Rädler, & G. Rüdiger (Dordrecht: Kluwer), 305
Krause, F., & Beck, R. 1998, A&A, 335, 789
Krause, M., Hummel, E., & Beck, R. 1989, A&A, 217, 4
Krause, M., Wielebinski, R., & Dumke, M., 2006, A&A, 448, 133
Niklas, S., & Beck, R. 1997, A&A, 320, 54
Rupen, M. P. 1991, AJ, 102, 48
Ruzmaikin, A. A., Shukurov, A. M., & Sokoloff, D. D. 1988, Magnetic Fields of Galaxies (Dordrecht: Kluwer)
Soida, M. 2005, in The Magnetized Plasma in Galaxy Evolution, ed. K. Chyży, K. Otmianowska-Mazur, M. Soida & R.-J. Dettmar, 185
Stil, J. M., Krause, M., Beck, R., & Taylor, A. R. 2008, A&A, in press, arXiv:0802.1374
Sukumar, S., & Allen, R. J. 1991, ApJ, 382, 100
Sur, S., Shukurov, A., & Subramanian, K. 2007, MNRAS, 377, 874