The Astrophysical Journal, 677: L17–L20, 2008 April 10

DISCOVERY OF A STRONG SPIRAL MAGNETIC FIELD CROSSING THE INNER PSEUDORING OF NGC 4736

Krzysztof T. Chyży[1] and Ronald J. Buta[2]

Received 2007 December 20; accepted 2008 March 3; published 2008 March 17

ABSTRACT

We report the discovery of a coherent magnetic *spiral* structure within the nearby *ringed* Sab galaxy NGC 4736. High-sensitivity radio polarimetric data obtained with the VLA at 8.46 and 4.86 GHz show a distinct ring of *total* radio emission precisely corresponding to the bright inner pseudoring visible in other wavelengths. However, unlike the total radio emission, the *polarized* radio emission reveals a clear pattern of ordered magnetic field of spiral shape, emerging from the galactic center. The magnetic vectors do not follow the tightly wrapped spiral arms that characterize the inner pseudoring, but instead cross the ring with a constant and large pitch angle of about 35°. The ordered field is thus not locally adjusted to the pattern of star formation activity, unlike what is usually observed in grand-design spirals. The observed asymmetric distribution of Faraday rotation suggests the possible action of a large-scale MHD dynamo. The strong magnetic total and regular field within the ring (up to 30 and 13 μG, respectively) indicates that a highly efficient process of magnetic field amplification is under way, probably related to secular evolutionary processes in the galaxy.

Subject headings: galaxies: evolution — galaxies: individual (NGC 4736) — galaxies: ISM — galaxies: magnetic fields — MHD — radio continuum: galaxies

1. INTRODUCTION

During the last decade, galactic magnetic fields have been observed in detail in a number of galaxies, from the grand-design and barred spirals to the dwarf irregulars (Beck 2005; Chyży et al. 2000). However, the role of magnetic fields in the dynamical evolution of galaxies and their interstellar medium (ISM), and the conditions and efficiency of the magnetic field generation process, are still not well understood. It is also unclear how the magnetohydrodynamic (MHD) dynamo interplays with gas flows associated with spiral density waves (Elstner 2005; Shukurov 2005). In grand-design spirals the magnetic field pitch angle adjusts to the high concentration of star formation in the spiral arms as, e.g., in NGC 6946 (Beck 2007), or in perturbed NGC 4254 (Chyży et al. 2007). But in flocculent galaxies, the possibly dynamo-generated magnetic field shows a large pitch angle (25°–30°), that sometimes agrees with optical armlets, and sometimes not (Knapik et al. 2000).

In contrast to grand-design spirals and many barred galaxies dominated by the spiral arms there are some early-type galaxies classified by de Vaucouleurs as "SA(r)" which are purely dominated by rings. Unlike spiral arms, galactic rings are believed to be formed by resonant accumulation of gas in the nonaxisymmetric potential of galaxies (Buta & Combes 1996; Buta et al. 2007). Under the continuous action of gravity torques gas is driven into resonance regions whose shape and orientation can be determined by the properties of periodic orbits (e.g., Regan & Teuben 2004). Such galaxies of ringed morphology and resonant dynamics can be excellent targets to address the above questions of galactic magnetism. Without strong spiral density waves and associated streaming motions they can complete our knowledge about the dynamo process in galaxies showing no grand-design spiral patterns.

Motivated by these goals we performed radio polarimetric observations of NGC 4736 (M94), the nearest and largest galaxy in the sky to manifest a strong ringed morphology. Classified as type (R)S$\underline{\text{A}}$B($\underline{\text{r}}$s)ab by Buta et al. (2007) it shows two rings. The outer ring (R) is a weak, diffuse, and smooth feature. But the inner pseudoring ($\underline{\text{r}}$s) is a well-defined zone of intense active star formation visible in optical, Hα, UV emission (Waller et al. 2001), and in infrared (Fig. 1) and CO maps (Wong & Blitz 2000). The inner ring extends to a radial distance of about 47″ (1.1 kpc)[3] around the galaxy (LINER) nucleus. NGC 4736 is not completely axisymmetric but has a large-scale, broad oval that may affect its internal dynamics (Kormendy & Kennicutt 2004). Hydrodynamic simulations suggest that the rotating oval is indeed responsible for the rings' formation (Mulder & Combes 1996). The nuclear minibar, well visible in CO emission as a central 20″ extension perpendicular to the galaxy major axis, may also participate in the ring formation process (Wong & Blitz 2000).

2. RADIO OBSERVATIONS AND RESULTS

We observed NGC 4736 between 2007 April 8 and May 16 at 8.46 and 4.86 GHz with the Very Large Array (VLA[4]) in its D-configuration. The data obtained were reduced, calibrated, and self-calibrated with the standard AIPS package. The allocated observing time of 33 hr enabled us to get high-sensitivity radio maps: in the polarized intensity we reached an rms noise level of 6 μJy beam^{-1} at 8.46 GHz in an 8.6″ × 8.6″ resolution map, and likewise 12 μJy beam^{-1} at 4.86 GHz in a 15″ × 15″ resolution map.

To avoid the missing-spacing problem, we also made radio polarimetric observations of NGC 4736 with the Effelsberg 100 m telescope at frequencies of 8.35 and 4.85 GHz. The data reduction and merging with the interferometric data were performed in a manner similar to NGC 4254 (Chyży et al. 2007). The combined maps in *I*, *Q*, and *U* Stokes parameters at both frequencies were then used to construct maps of polarized intensity, polarization position angle, position angle of observed magnetic vectors (observed *E*-vectors rotated by 90°), and Faraday rotation measure.

[1] Astronomical Observatory, Jagiellonian University, 30-244 Kraków, Poland; chris@oa.uj.edu.pl.

[2] Department of Physics and Astronomy, University of Alabama, Tuscaloosa, AL 35487.

[3] We adopt a distance of 4.66 Mpc (Karachentsev et al. 2004).

[4] The VLA of the NRAO is operated by Associated Universities, Inc., under cooperative agreement with the NSF.

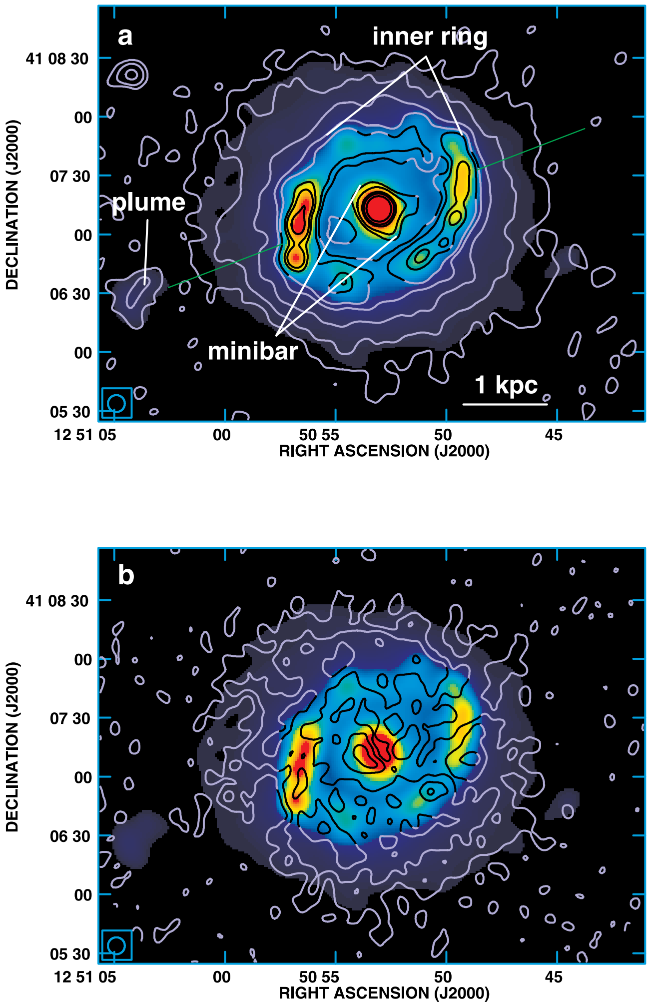

FIG. 1.—(*a*) Total radio intensity contour map of NGC 4736 at 8.46 GHz and 8.6″ × 8.6″ resolution (from combined VLA and Effelsberg data) superimposed on the infrared 24 μm image (in colors, from *Spitzer* survey of SINGS galaxies: Kennicutt et al. 2003). The contours are at 28, 72, 176, 320, 440, 800, 1040, and 1600 μJy beam^{-1}. (*b*) Radio polarized intensity at 8.46 GHz in contours and the infrared map in colors. The contours are at 21, 42, 70, and 98 μJy beam^{-1}. The galaxy is inclined by 35° (Buta 1988) and the green line in (*a*) denotes its major axis. The inner (r̲s) ring and the central minibar are indicated, whereas the faint, outer (R) ring̲ is out of the figure and also invisible in the radio data.

The observed total radio emission of NGC 4736 at 8.46 GHz is clearly dominated by the galaxy's bright inner pseudoring (Fig. 1*a*) and resembles the distributions of infrared, Hα, and UV emission (e.g., Waller et al. 2001). All pronounced radio features in the ring correspond to the enhanced signal in the mid-infrared (in colors in Fig. 1*a*) and must result from an intense star formation process providing dust heating and strong radio thermal and nonthermal emission. The radio contours in the galaxy's bright bulge region (within 20″ radius) are slightly elongated in position angle P.A. ≈ 30°. They likely correspond to the nuclear minibar seen in optical and CO images (§ 1). Outside the galaxy's bright radio disk, weak radio emission is detected from a star-forming plume (Fig. 1*a*), being another feature of the galaxy's resonant dynamics (Waller et al. 2001).

The polarized radio emission of NGC 4736 at 8.46 GHz reveals a dramatically different morphology (Fig. 1*b*). It does not clearly correspond either to the inner pseudoring in the infrared emission or to the distribution of total radio emission.

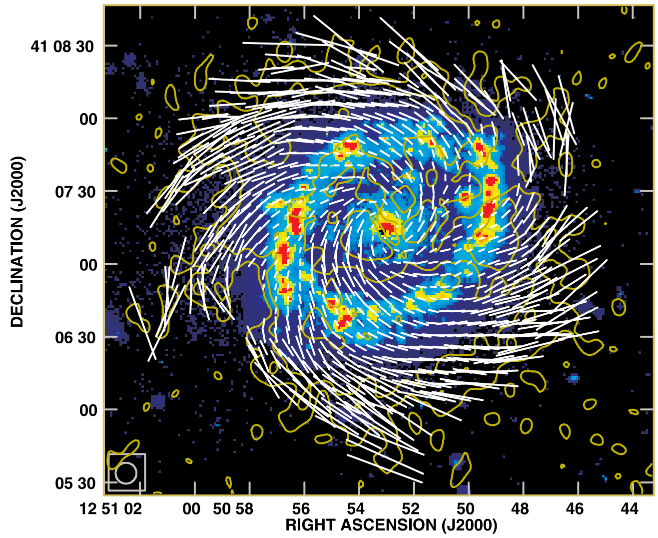

FIG. 2.—Polarized intensity contour map of NGC 4736 at 8.46 GHz and 8.6″ × 8.6″ resolution with observed magnetic field vectors of the polarization degree overlaid on the Hα image (from Knapen et al. 2003). The contours are at 21, 42, and 84 μJy beam^{-1} area. The vector of 10″ corresponds to the polarization degree of 25%.

The degree of polarization is slightly lower in the ring (about 10% ± 1% on average) than in its close vicinity (15% ± 1%), and rises to about 40% at the disk edges. The observed vectors of regular magnetic field (Fig. 2) are organized into a very clear spiral pattern with two broad magnetic arms. Surprisingly, the inner ring hardly influences the magnetic vectors: they seem to cross the star-forming regions without any change of their orientation. This is opposite to what is observed in grand-design spiral galaxies (§ 1), where the magnetic field typically follows a nearby spiral density wave.

The revealed spiral magnetic pattern at 8.46 GHz, is fully confirmed at 4.86 GHz. The observed similar orientation of magnetic field vectors at both radio frequencies indicates only small Faraday rotation effects in this galaxy (see below). Hence, the magnetic vectors presented in Figure 2 give almost precisely the intrinsic direction of the projected magnetic field (within 7°) in most of the galactic regions.

3. PURE DYNAMO ACTION?

The observed spiral structure of the magnetic field in NGC 4736 contradicts the main feature of its optical morphology: the starbursting inner pseudoring. To investigate the exact pattern of regular magnetic field without projection effects, we constructed a phase diagram (Fig. 3) of magnetic field vectors along the azimuthal angle in the galaxy plane versus the natural logarithm of the galactocentric radius. It confirms that the magnetic vectors cross the Hα-emitting ring (which constitutes a horizontal structure in Fig. 3) without changing their large pitch angle of 35° ± 5°. The two broad magnetic spiral arms (§ 2) clearly emerge from close to the galactic center, at azimuths of about 0° and 180°. Inside the inner ring, around azimuths of 120° and 300°, the magnetic pitch angle attains smaller values, from 0° to 20°, which may result from gas flows around the central minibar (§ 1). Despite this, the observed pattern of regular field in NGC 4736 seems to be the most coherent one observed so far in spiral galaxies (cf. Beck 2005).

The comparison of the magnetic pattern in NGC 4736 with the *Hubble Space Telescope* and other filtered optical images

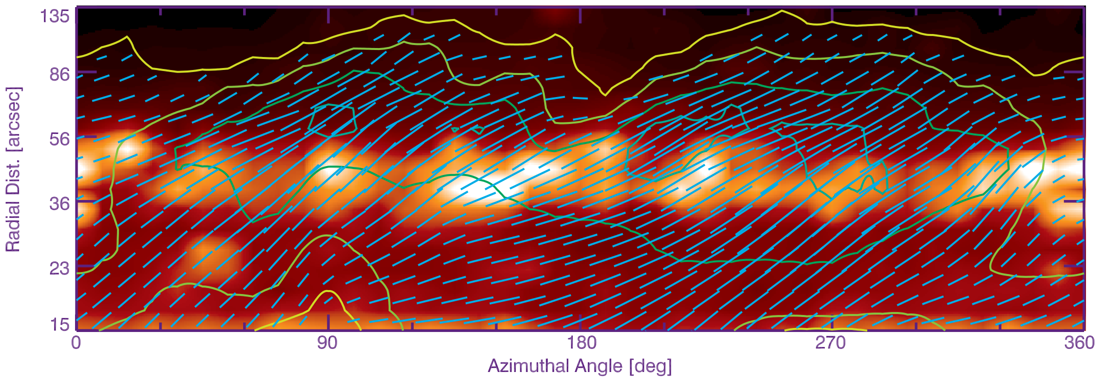

FIG. 3.—Diagram of the deprojected regular magnetic field vectors in the plane of NGC 4736 at 8.46 GHz (without correction for Faraday effects). The galactocentric azimuthal angle is measured counterclockwise from the northern tip of the major axis (P.A. = 295°). The vector's length is proportional to the polarized intensity, also presented in contours. The Hα image is shown in colors.

indicates further disagreement of the regular magnetic field with other galactic structures, e.g., the prominent, almost circular, long dust lane west of the center (Waller et al. 2001), or spiral dust armlets (probably of acoustic origin) in the central part of the galaxy (Elmegreen et al. 2002). Outside the ring, the relation of magnetic vectors with optical, flocculent features (Waller et al. 2001) is ambiguous, and contrary to the magnetic structure the optical features do not continue inside the ring. The kinematics of CO- and H I–emitting gas near the ring is well described by pure circular differential rotation with a velocity of about 200 km s^{-1} and small residuals, typically less than about 10 km s^{-1} (Wong & Blitz 2000). This assures that galactic shearing motions in the vicinity of the inner ring are strong. Hence, the observed magnetic spiral could result from a *pure* MHD dynamo action that develops without support from spiral density waves (§ 1).

The strongest observational test for the origin of the galactic magnetic field is the distribution of Faraday rotation measure (RM), which is sensitive to the sense of direction of the magnetic field. Magnetic fields produced locally by ejections from stars or by small-scale MHD dynamos, compressed in shocks or stretched by gas shearing flows, yield random fields and incoherent (changing sign) RM patterns. Only the large-scale dynamo can induce unidirectional magnetic field and produce a coherent RM pattern on the galactic scale. The typical RM values observed in NGC 4736 (Fig. 4) are small, about ± 50 rad m^{-2}, reaching locally $|RM| > 100$ rad m^{-2}. As the galaxy is located at high Galactic latitude (76°) the influence of the Milky Way on observed RM could be omitted. Globally, NGC 4736 shows a large area of statistically positive RM in the northwestern part of the galaxy and negative RM in the southeastern one. This gives a strong argument for a large-scale MHD dynamo working in this object.

From maps of total and polarized emission and the direction of magnetic field vectors corrected for Faraday rotation we derive "magnetic maps" (Chyży 2008)—the strength of total, random, and regular magnetic field throughout the galaxy plane, corrected for projection effects. In calculations we assume equipartition between the energy of the magnetic field and cosmic rays with an $E = 300$ MeV cutoff in the cosmic-ray proton spectrum, the energy ratio $k = 100$ of cosmic-ray protons and electrons, and an unprojected synchrotron disk thickness of $L = 500$ pc. The thermal emission is separated from the observed radio intensity assuming a nonthermal spectral index of 0.9. The total magnetic field (Fig. 5*a*) is strongest in the galactic center and in the starbursting ring where its strength varies from 18 to even 30 μG. The field is dominated by the random component (Fig. 5*b*) which roughly correlates with star-forming regions of Hα emission, as also seen in other galaxies. Contrary to the random component the regular magnetic field (Fig. 5*c*) is strongest in the southern part of the ring and in the regions outside the ring, reaching locally 13 μG. These local values are similar to the largest ones found in the nonbarred late-type spirals (Beck 2005).

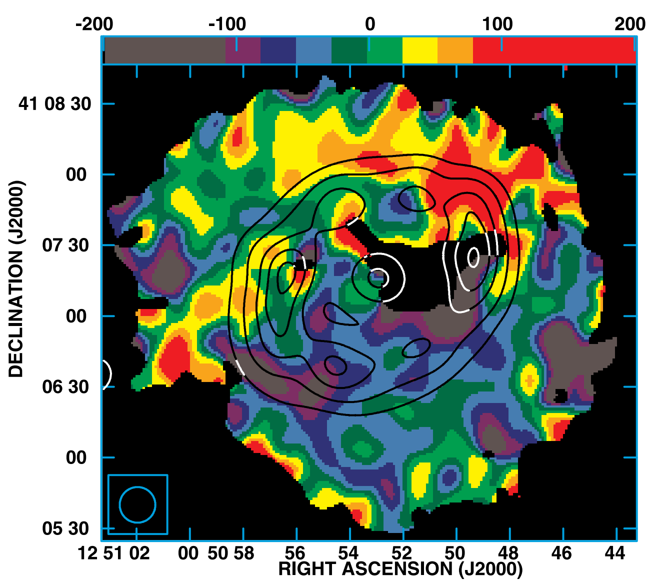

FIG. 4.—Faraday rotation measure distribution (in colors) of NGC 4736, at 15″ resolution, computed from 8.46 and 4.86 GHz data, in rad m^{-2}, with contours of Hα emission.

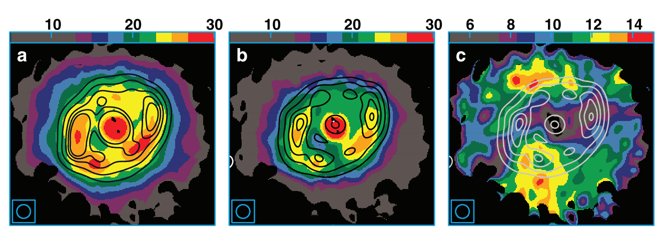

FIG. 5.—Magnetic maps of NGC 4736. (*a*) Total, (*b*) random, and (*c*) regular magnetic field strength (in μG) in colors, with contours of (*a*) infrared 24 μm and (*b*, *c*) Hα emission.

The mean total and regular field within the radio extent of NGC 4736 (of ≈3.5′) is 17 and 10 μG, respectively. These mean values are much larger than the averages found for spiral galaxies of various types (9 and 4 μG, respectively; Beck 2005). Our estimates of magnetic field strengths for NGC 4736 depend somewhat on the assumptions given above. If instead of equipartition, pressure equilibrium is assumed (yielding minimum stable magnetic field), its strength is lowered by about 25%. The magnetic field may vary by the same amount if the values of E, k, and L are varied independently by 50%. We thus conclude that the MHD dynamo in NGC 4736 must be very efficient.

4. ORIGIN OF MAGNETIC FIELD

We have shown that the spiral pattern of regular magnetic field lines in NGC 4736 is not coupled to any gas distribution features or recognized gas flows and can be of pure dynamo origin, unlike those of grand-design spirals (§ 3). The map of Faraday rotation (Fig. 4) confirms that some large-scale dynamo must be at work. If a freely evolving dynamo, without strong support from spiral density waves, produces a spiral field like that seen in NGC 4736, then such a dynamo could also explain magnetic spiral patterns found in several flocculent galaxies lacking obvious spiral density waves (§ 1).

Observations of NGC 4736 can also help in understanding the spiral magnetic field revealed in the area of the circumnuclear ring of NGC 1097 (Beck et al. 1999), a barred spiral galaxy strongly interacting with a nearby companion (see Buta et al. 2007). According to a recent interpretation (Prieto et al. 2005), the nuclear magnetic spiral in this galaxy is coupled to extraplanar gas. Such an explanation does not seem likely for the spiral magnetic field in NGC 4736 due to the very coherent magnetic pattern and small depolarization effects in the ring. Also, NGC 4736 is a relatively isolated galaxy, suggesting that internal dynamics play a more important role. The spiral fields around the star-forming rings in both galaxies could therefore be of different origins. But the alternative scenario that the structure of the magnetic field in the center of NGC 1097 may be dominated by a pure dynamo action (as in NGC 4736) could also be valid. Indeed, unlike the bar region and beyond, strong density waves in NGC 1097 are largely absent inside the circumnuclear ring.

The high efficiency of the dynamo amplification process in NGC 4736 is surprising for such an early-type object, because in another early-type spiral, the Sombrero galaxy NGC 4594, the magnetic field is 4 times weaker and reaches locally 6 μG in the total and only 3 μG in the regular component (Krause et al. 2006). The cause for this discrepancy may lie in different galaxy evolutions. While NGC 4594 has a classical bulge, NGC 4736 contains a prototypical pseudobulge (Kormendy & Kennicutt 2004), with different Sérsic index n in the luminosity profile $\log I \propto r^{1/n}$ and a larger flattening, revealing much more regular (disky) rotation. Thus the secular evolution of NGC 4736, which also led to formation of the starbursting pseudoring, might affect the magnetic field generation and evolution, and account for the observed difference between the two galaxies.

The reported large pitch angle of the regular magnetic field in NGC 4736 (35°; Fig. 3) demands special conditions for the dynamo to be set up. According to the MHD simulation by Elstner et al. (2000), in typical spiral galaxies the large pitch angles (>20°) are supported by spiral density waves. These are, however, weak in NGC 4736, and in the region of its inner ring they become almost circular. For $\alpha\Omega$-dynamos with α-quenching one has a dependence of the magnetic pitch angle p on the turbulent diffusivity η_T, the disk scale height h, the turnover radius r_Ω in the rotation curve, and the rotational velocity v (Elstner 2005): $\tan p \approx 3r_\Omega\eta_T/(vh^2)$. With $r_\Omega = 440$ pc and $v = 200$ km s^{-1} (estimated from the CO and H I rotation curve; Wong & Blitz 2000), and with typically used values for late-type spirals of $\eta_T = 1$ kpc km s^{-1} and $h = 500$ pc, we get $p = 2°$, much less than the observed value. To produce larger p by a pure dynamo process, a larger magnetic diffusivity or thinner gaseous disk is necessary. The Hα and synchrotron scale heights of the ring are 370 and 480 pc, respectively (cf. Fig. 1). Thus, the disk scale height is unlikely to be ≲300 pc, which leads to a needed turbulent diffusion of at least 10 kpc km s^{-1}. Such conditions could likely be achieved in the violently star-forming inner ring with the support of, e.g., a strong diffusion of CRs, as in the fast Parker's cosmic-ray-driven dynamo (Hanasz et al. 2004). The fact that the radio polarized emission is so highly restricted to the vicinity of the starbursting ring (Fig. 2) provides another stringent constraint on the dynamo action. Thus, NGC 4736 is an excellent object to test the most recent concepts of MHD dynamos.

In this report we have demonstrated that the early-type galaxy NGC 4736 has highly symmetric and strong magnetic spiral fields, not clearly associated with the shape of the distribution of star-forming regions or with spiral density waves. The detailed processes which cause the dynamo in NGC 4736 to run so efficiently and enable the generated regular field to ignore the galaxy's ringed morphology remain to be determined.

We thank R. Beck for help in gathering the Effelsberg data and R. Beck, D. Elstner, M. Krause, K. Otmianowska-Mazur, M. Urbanik, and the referee for helpful comments. K. T. C. acknowledges the support of MNiSW grant 2693/H03/2006/31 and R. J. B. the support of NSF grant AST 050-7140.

REFERENCES

Beck, R. 2005, in Cosmic Magnetic Fields, ed. R. Wielebinski & R. Beck (Heidelberg: Springer), 41
———. 2007, A&A, 470, 539
Beck, R., et al. 1999, Nature, 397, 324
Buta, R. 1988, ApJS, 66, 233
Buta, R., & Combes, F. 1996, Fundam. Cosmic Phys., 17, 95
Buta, R., Corwin, H. G., & Odewahn, S. C. 2007, The de Vaucouleurs Atlas of Galaxies (Cambridge: Cambridge Univ. Press)
Chyży, K. T. 2008, A&A, in press (arXiv:0712.4175)
Chyży, K. T., Beck, R., Kohle, S., Klein, U., & Urbanik, M. 2000, A&A, 355, 128
Chyży, K. T., Ehle, M., & Beck, R. 2007, A&A, 474, 415
Elmegreen, D. M., Elmegreen, B. G., & Eberwein, K. S. 2002, ApJ, 564, 234
Elstner, D. 2005, in The Magnetized Plasma in Galaxy Evolution, ed. K. T. Chyży (Kraków: Obs. Astron.), 117
Elstner, D., et al. 2000, A&A, 357, 129
Hanasz, M., et al. 2004, ApJ, 605, L33
Karachentsev, I. D., et al. 2004, AJ, 127, 2031
Kennicutt, R. C., et al. 2003, PASP, 115, 928
Knapen, J. H., et al. 2003, MNRAS, 344, 527
Knapik, J., et al. 2000, A&A, 362, 910
Kormendy, J., & Kennicutt, R. C. 2004, ARA&A, 42, 603
Krause, M., Wielebinski, R., & Dumke, M. 2006, A&A, 448, 133
Mulder, P. S., & Combes, F. 1996, A&A, 313, 723
Prieto, M. A., Maciejewski, W., & Reunanen, J. 2005, AJ, 130, 1472
Regan, M., & Teuben, P. 2004, ApJ, 600, 595
Shukurov, A. 2005, in Cosmic Magnetic Fields, ed. R. Wielebinski & R. Beck (Heidelberg: Springer), 113
Waller, H. W., et al. 2001, AJ, 121, 1395
Wong, T., & Blitz, L. 2000, ApJ, 540, 771