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Magnetic diagnostics of interacting and merging galaxies

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Abstract

Magnetic fields, especially the ordered ones observed using the radio polarimetry constitute a very sensitive indicator of anomalous gas flows in perturbed galaxies. In contrast to methods based on radial velocities, the deformations of magnetic fields provide at least qualitative estimate of gas flow directions *in the sky plane*. We present examples of the "magnetic diagnostics" in case of various kinds of interactions: the merging galaxies and those interacting with their environment in clusters and groups. The case of an apparently isolated galaxy whose magnetic fields still shows traces of past interactions is discussed as well.

1 Introduction

Most of galaxies show various degrees of interactions with their environment, the isolated ones being really rare. Though it is clear that the environmental effects play a crucial role in the galaxy evolution e.g. by driving the density waves (Kormendy & Norman 1979) or triggering starbursts (Barton et al. 2000), we are still far from understanding complex hydrodynamical processes accompanying galactic interactions.

The radio polarimetry measures the geometry of ordered magnetic fields (either unidirectional – called regular or compressed random ones) perpendicular to the line of sight. It is thus sensitive to perturbations of magnetic field structure caused by sky-parallel peculiar gas flows. This offers the possibility of at least qualitative estimates of directions of sky-parallel gas flow anomalies, complementing the radial velocity information. The magnetic asymmetries caused by interactions were first discovered by Hummel and Beck (1995). Below we present examples of galaxies in which studying the radio polarization provides some information on peculiarities of the gas kinematics in the sky plane. As we show, magnetic fields also constitute a long-lasting memory of weak past interactions which at present leave no obvious anomalies in the gas distribution and kinematics.

2 Merging galaxies

The galaxy pair NGC 4038/NGC 4039, called "The Antennae" is an excellent example of merging spirals with two impressive optical tidal tails. A long H I extension along the southern tail has been observed by Hibbard et al. (2001). The young star clusters are distributed along a peculiar structure, encircling the northern galaxy from the west, running towards the east along the northern and northeastern edge of the whole system. A huge complex of cold dusty matter extends between the galaxies (Haas et al. 2000).

Chyży & Beck (2004) using VLA observations of NGC 4038/39 at three frequencies identified a number of physically distinct regions with different radio and polarization properties. The huge dark cloud between the galaxies is found to host relatively well-ordered magnetic fields (especially in its northern part, Fig. 1). The field structure is coherent over the whole

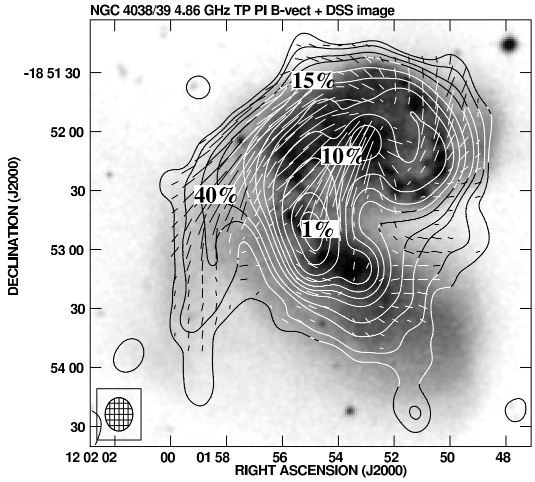

Figure 1: The total power contours and B-vectors of polarized intensity of merging galaxies NGC 4038/39 observed using VLA D-array at 4.86 GHz, overlaid upon the blue DSS image (Chyży and Beck 2004). The contour levels are (3, 8, 20, 35, 80, 140, 220, 350, 600, 1100, 1600)$\times$15 μJy/b.a.. The polarization vector of $1'$ denotes the polarized intensity of 0.75 mJy/b.a.. The numbers show the polarization degree in selected areas

length of the cloud, comparable to the distance between the galaxies. The regular field is aligned with the major axis of the cloud and may be the result of magnetic field compression along the collision line between the galaxies. In the southern part of the dark cloud the polarization degree drops down by a factor of 10 while the total power emission forms a strong peak. In this region Haas et al. (2000) found the warm dust emission to be stronger than in the northern part of the cloud. The ordered field enhanced by the collision between the gaseous disks of the galaxies is probably destroyed in the southern region by an optically invisible star formation burst. The radio polarization observations are in this case very helpful in identifying the compression region at the collision line between the galaxies together with a hidden (compression- triggered?) star-forming nest in its southern part.

The polarization degree of NGC 4038/39 at 4.86 GHz rises strongly up to 40% at the base of a gas-rich tidal tail (Fig. 1). The same region shows a significant steepening of the radio spectral index to slopes higher than 1.3 (Chyży and Beck 2004). The quoted authors suggest a picture in which the cosmic-ray electrons are ageing being taken with a magnetized gas outflow away from their sources. The magnetic field is also pulled away from turbulent regions and gets more ordered probably via reconnection processes. It seems therefore that a substantial amount of magnetic fields, primarily regular ones, is supplied to the intergalactic space by merging galaxies. Galaxy collisions were very frequent in early Universe providing an important source of regular intergalactic magnetic fields.

3 Cluster galaxies

3.1 The weakly affected spiral NGC 4254

NGC 4254 is a Virgo Cluster Sc spiral showing no obvious effects of H I stripping by the intergalactic gas (Cayatte et al. 1994). It is located outside of the X-ray emitting intracluster gas cloud (Böhringer et al. 1997). Though NGC 4254 is somewhat asymmetric with a heavy southern arm this galaxy does not show strong signs of interactions. However, its VLA map at 8.46 GHz (Fig. 2, Chyży et al. in prep.) shows a ridge of polarized emission along the southern arm. It is the brightest polarization feature in this galaxy. Unlike the frequently observed concentration of polarization in the interarm region (Beck 2004) the bright polarized

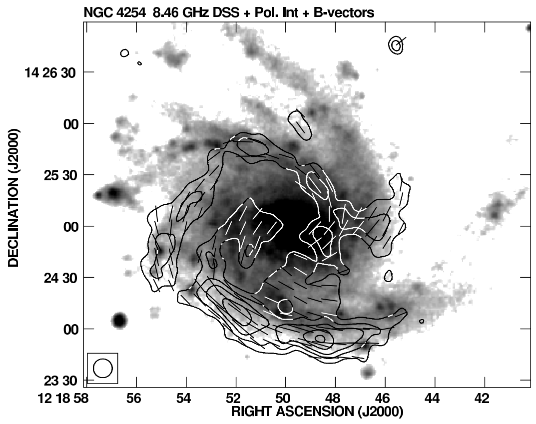

Figure 2: The contours and B-vectors of brightest polarized features in NGC 4254 at 8.46 GHz observed by the VLA D-array overlaid upon the digitally enhanced blue DSS image (Chyży et al. in prep.). The contour levels are (6, 9, 12, 16, 20)$\times$ 8μJy/b.a. The polarization vector of 1$'$ denotes the polarized intensity of 0.43 mJy/b.a..

ridge is situated *outside* of the optical arm. We suspect that it may be due to compression from the infalling intracluster gas. A detailed analysis of the polarization maps taking into account all the extended emission shows a specific asymmetry of magnetic pitch angles: the magnetic field is almost azimuthal in the southern disk while its pitch angle reaches some 40°– 45° in the northern disk. The polarized intensity also has a radial scale larger by some 50% in the northern than in the southern disk. Numerical models (Otmianowska-Mazur & Vollmer 2003) demonstrate that the polarized ridge, as well as the asymmetry of magnetic pitch angles and of radial scale of polarized emission constitute typical signatures of a late phase of interaction with the intracluster gas. They occur during the reaccretion of the gas stripped away some 500-600 Myr ago. While at this stage little effects of interactions remain in the optical structure, the magnetic field shows strong anomalies, constituting a long-lasting memory of past stripping effects.

3.2 The intermediate case – NGC 4501

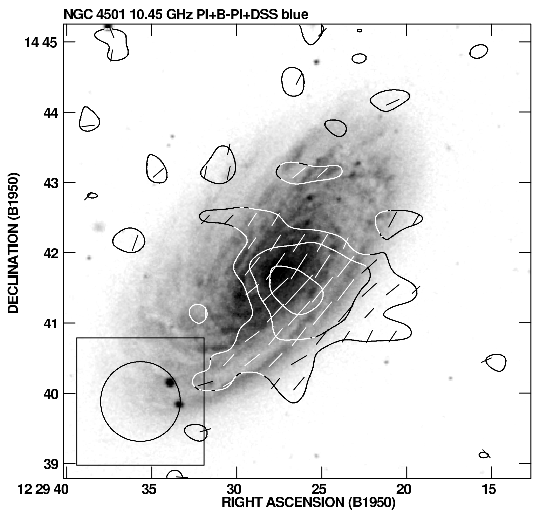

Figure 3: The map of polarized intensity with B-vectors of the same quantity of NGC 4501 observed with the Effelsberg radio telescope at 10.45 GHz overlaid upon the blue DSS image (Chyży et al. in prep.). The contour levels are (3, 6, 9)$\times$0.3 mJy/b.a., the polarization vector of 1$'$ denotes the polarized intensity of 6 mJy/b.a.

NGC 4501 is an Sb galaxy located NE of the Virgo Cluster centre. It shows moderate signs of H I deficiency (Cayatte et al. 1994) and a clear asymmetry of the gaseous disk (Cayatte et al. 1990). An X-ray peak has been found by Böhringer et al. (1997) outside of the disk edge showing effects of H I compression (Cayatte et al. 1990). Our Effelsberg observations at 10.45 GHz (Fig. 3) show a bright peak of polarized emission shifted towards the disk edge showing effects of H I compression and the X-ray peak. The integration of the polarized signal in rectangular areas NE and SW of the major axis shows that about 85% of the polarized flux comes from the disk half suspected to undergo interaction with the ambient gas. A too low resolution ($1\farcm2$) of these observations inhibits a clear identification of the polarized compression region. We note however that a narrow polarized ridge in NGC 4254 seen clearly by the VLA (Fig. 2) also looked only as a strong concentration of polarized emission on one disk side when observed by Soida et al. (1996) using the Effelsberg radio telescope with a beam of $1\farcm2$. We suspect that NGC 4501 may possess a ridge of polarized emission along its SW disk edge, too.

3.3 The strongly stripped spiral – NGC 4569

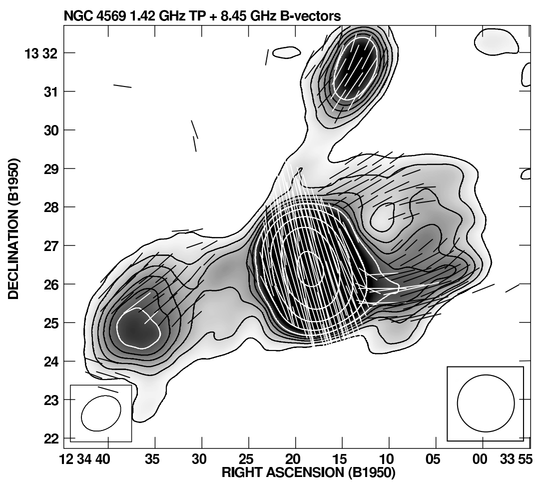

Figure 4: A combined image showing the distribution of total power emission at 1.49 GHz (contours and grayscale) and orientations of polarization B- vectors at 8.45 GHz. The total power map is made from continuum residuals after subtraction of the H I signal from the observations of Vollmer et al. (2004), the B-vectors are from the observations with the Effelsberg radio telescope (Chyży et al. 2005). The contour levels are 1, 1.5, 2, 2.5, 3, 3.5, 5, 10, 20, 40 mJy/b.a. The beams of the total power and polarization maps are shown in the left and right lower corner respectively

NGC 4569, an Sb galaxy at an angular distance of 1^o from the Virgo Cluster core, shows strong signatures of stripping by the intergalactic gas (Cayatte et al. 1990, 1994). Chyży et al. (2005) using the Effelsberg radio telescope at 4.85 GHz and 8.45 GHz discovered large radio lobes with vertical magnetic fields extending by more than 20 kpc from the disk. Their existence is confirmed by the radio continuum map at 1.4 GHz made from residuals of H I observations of Vollmer et al. (2004). A superposition of the mentioned data is shown in Fig. 4. The western lobe coincides with an extended region of X-ray emission (Tschöke et al. 2001). Such large vertical structures are unusual for a spiral galaxy.

Discussing the nature of these outflows in NGC 4569 (black hole-powered nucleus, Barth & Shields 2000, central starburst-driven outflow, Tschöke et al. 2001 or stripping by the intracluster medium, Vollmer et al. 2001) is beyond the scope of this article. We note however that the southern part of the western lobe contains a narrow radio ridge, probably smaller in width than $1'$ (the beam size perpendicular to the ridge). This region is substantially polarized at 8.45 GHz, on average by some 23$\pm$5%, with magnetic lines running along the ridge. It is also the brightest polarized feature in the lobes. Independently of the nature of unusual extraplanar radio emission in NGC 4569, the existence of a narrow, highly polarized radio ridge may again constitute a signature of interaction with the ambient gas.

We present here three examples of galaxies with various degrees of interaction with the intracluster medium. All of them show enhancements of polarized emission on one side of the disk (NGC 4569, NGC 4501) or in extended extraplanar radio lobes (NGC 4569). In all cases it happens in the direction towards M87 thought to mark the centre of Virgo Cluster. A hypothesis that the radio polarization is a sensitive tracer of perturbations by the ambient medium seems attractive. It may help in verifying the models of such interactions (see Otmianowska-Mazur et al. 2003).

4 Galaxies in loose groups and isolated spirals

4.1 The Leo Triplet member NGC 3627

NGC 3627 is an SBb galaxy interacting tidally within the Leo Triplet group (e.g. Haynes et al. 1979). In addition to a bar it possesses two asymmetric spiral arms showing strong density wave effects. The galaxy shows only mild optical asymmetries: the western arm showing only weak traces of star formation is long and almost straight. The eastern arm is shorter, considerably bent inwards and contains an actively star-forming straight segment.

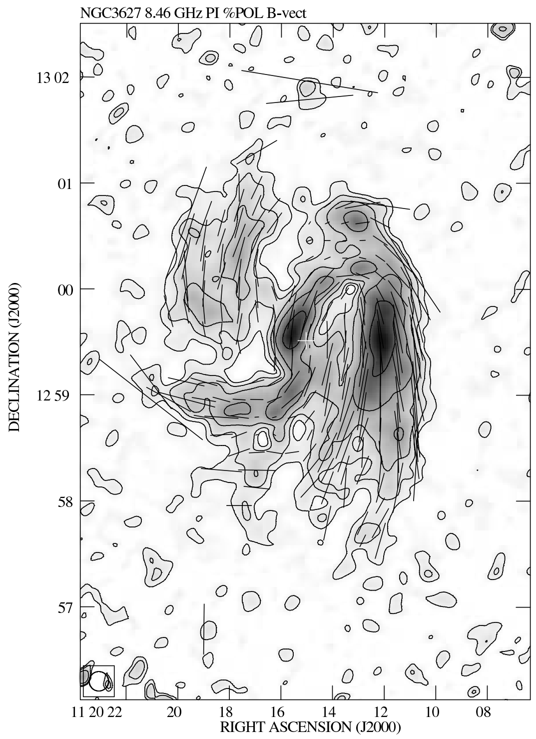

Figure 5: The grayscale and contours of polarized intensity with apparent B-vectors of polarization degree of NGC 3627 at 8.46 GHz (VLA D-array, Soida et al. 2001). The contour levels are (3, 5, 8, 13, 21)*8 μJy/b.a.. A polarization vector of $1'$ length corresponds to a polarization degree of 60%. A white cross denotes the optical disk centre

Soida et al. (2001) observing with the VLA at 8.46 GHz and 4.85 GHz revealed two distinct components of the magnetic field of NGC 3627: a spiral arm/bar component and a diffuse one extending into the interarm region. They also found that the brightest polarized feature in NGC 3627 is an elongated peak of polarized emission in the western spiral arm (Fig. 5). This side of the disk shows also a much steeper gradient in total power than the eastern one. The analysis of magnetic field orientations also reveals a pronounced asymmetry in the magnetic pitch angle ψ. While in the western disk half the mean $\psi \approx 16 \pm 4°$, east of the major axis $\psi \approx 35 \pm 3°$, more than twice larger. In the western interarm region $\psi \approx 16 \pm 2°$compared to $27{\pm}2°$in its eastern counterpart, the pitch angle differences are thus not caused by any asymmetries of the spiral arm component.

The H I image made by Haynes et al. (1979) shows a long gaseous plume extending from NGC 3628 towards the western region of NGC 3627. The latter galaxy also has a steep boundary of the H I disk on the western side and a gaseous plume extending to the east. Our radio and polarization data allow us to propose a consistent picture of the gas infalling from the west (a bright polarized spot, compare also Sect. 3, and the magnetic field orientation much closer to azimuthal), possibly flowing towards the east. Observing the polarized emission also in this case helps in determining the direction of gas motions in the sky plane.

4.2 NGC 4414 - an isolated galaxy?

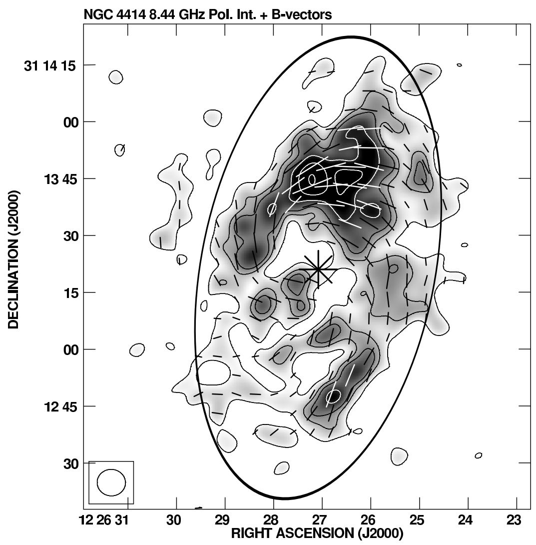

Figure 6: The high-resolution, uniformly weighted VLA D-array map of polarized intensity (contours and grayscale) with polarization B-vectors of NGC 4414 at 8.44 GHz observed by Soida et al. (2002). The contour levels are (3, 6, 8, 12, 16, 20)$\times$5.5 μJy/b.a.. The polarization vector of 1′ denotes the polarized intensity of 0.6 mJy/b.a.. A thick ellipse outlines the optical disk

NGC 4414 is a flocculent Sc galaxy, lacking a global spiral pattern. Its velocity field shows no evidence for non-circular gas flows (Braine et al. 1993, Sakamoto 1996, Thornley & Mundy 1997). Braine et al. (1997) discuss NGC 4414 as an example of an isolated spiral. Nevertheless its multifrequency VLA study by Soida et al. (2002) revealed pronounced asymmetries typical for interacting spirals. The uniformly weighted high-resolution (beam of 7″) map at 8.44 GHz shows that brightest polarized features are concentrated in the northern disk half (Fig. 6). A detailed analysis of naturally weighted maps (showing also the diffuse polarized emission) reveals also a strong asymmetry in magnetic pitch angles: the magnetic field is almost azimuthal in the northern disk while the pitch angle $\psi \approx$45° in the southern disk region. Soida et al. (2002) also report a radio tail extending southwards from the disk of NGC 4414. All the discussed anomalies resemble the signatures of interactions found in cluster and group spirals (see Sect. 3.1, 4.1). Similar asymmetries of polarized brightness, magnetic pitch angle and the radio tail are also observed in the wind-swept spiral NGC 2276 (Hummel & Beck 1995, Harnett et al. 2004, Condon 1983) and are suggestive for the infall of some yet unspecified matter from the north and its motion southwards.

Even more striking asymmetry is observed in the distribution of Faraday rotation of NGC 4414 (Soida et al. 2002). While in the northern disk the Faraday rotation measures (RM) do not exceed 70 rad/m^2, in its southern region the galaxy becomes "Faraday thick" with RM in excess of $\pm$600 rad/m^2. This has been explained by Soida et al. (2002) as due to a four times thicker layer of ionized gas in the southern disk, reaching 3 kpc. Additionally, a more than twice higher filling factor of the diffuse ionized gas than in the northern disk is required.

All these asymmetries are difficult to understand if NGC 4414 were really an isolated galaxy. The inner disk is unperturbed, as the total power emission shows a hole with no trace of any nuclear source nor of a central starburst. If anything has perturbed this galaxy, it had effects on outer disk regions only. Kornreich et al. (2001) found that while the optical morphology returns quickly to a symmetric appearance, the gas dynamics constitutes a long-lasting memory of past, weak perturbations. We present an example of a galaxy whose magnetic field still remembers the weak past interaction with an unspecified agent, now forgotten even by its gas kinematics.

5 Summary and conclusions

We demonstrate that observing the magnetic fields in perturbed galaxies via the radio polarization provides a very useful tool in studying their kinematics. In particular we show that:

- Observing the radio polarization of merging galaxies is a good tool to diagnose hidden star-formation bursts, large-scale collision-induced shocks and gas outflows pulling the regular, unidirectional magnetic fields into the intergalactic space

- In Virgo Cluster galaxies effects of large-scale compression were revealed, even in weakly stripped objects at the cluster periphery. The location of these compressed regions may help to establish the direction of galaxy motions with respect to the ambient medium *in the sky plane* which helps in constructing a three-dimensional picture of cluster kinematics.

- The radio polarization picture may also help in establishing the transversal gas flows in tidally interacting spirals

- The perturbations in the magnetic field structure also constitute a "long living memory" of past weak interactions in galaxies looking at present isolated and showing no obvious signs of perturbations in the optical structure nor in the gas kinematics

The mentioned information on the gas motions in the sky plane adds new dimensions to radial velocity studies. It also opens way to more quantitative modeling in which the parameters like the shock strength and/or the magnetic diffusivity can be constrained e.g. by observed contrasts of polarized emission and the magnetic field alignment with the velocity field. We believe that with the advent of more powerful telescopes like Square Kilometer Array the deep, high resolution polarization observations of high-redshift objects will help in solving many problems of galaxy and cluster formation at early cosmological epochs.

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