Magnetic fields and gas flows around circumnuclear starbursts

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Abstract. Radio continuum observations of barred galaxies revealed strong magnetic fields of $\geq 50 - 100\,\mu G$ in the circumnuclear starbursts. Such fields are dynamically important and give rise to magnetic stress that causes inflow of gas towards the center at a rate of several solar masses per year, possibly along the spiral field seen in radio polarization and as optical dust lanes. This may solve the long-standing question of how to feed active nuclei, and explain the relation between the bolometric luminosity of AGN nuclei and the star-formation rate of their hosts. The strong magnetic fields generated in young galaxies may serve as the link between star formation and accretion onto supermassive black holes. – Magnetic fields of $\geq 160\,\mu G$ strength were measured in the central region of the almost edge-on starburst galaxy NGC 253. Four filaments emerging from the inner disk delineate the boundaries of the central outflow cone of hot gas. Strong Faraday rotation of the polarized emission from the background disk indicates a large-scale helical field in the outflow walls.

1. Introduction
Magnetic fields are a major agent in the ISM and also control the density and propagation of cosmic rays. The radio–infrared correlation indicates that turbulent fields are strongest in star-forming regions. Magnetic fields and cosmic rays can provide the pressure to drive galactic outflows. Outflows from starburst galaxies in the early Universe may have magnetized the intergalactic medium. In spite of our increasing knowledge of cosmic magnetic fields, many important questions, especially their origin, strength in intergalactic space, first occurrence in young galaxies and their dynamical importance for galaxy evolution remain unanswered.

2. Origin of galactic magnetism
The most promising mechanism to sustain magnetic fields in the interstellar medium of galaxies is the dynamo. In young galaxies a small-scale dynamo probably amplified seed fields from the protogalactic phase to the energy density level of turbulence within less than $10^9\,\text{yr}$ (Schleicher et al. [24]). To explain the generation of large-scale fields in galaxies, the mean-field dynamo has been developed (Beck et al. [7]). It is based on turbulence, differential rotation and helical gas flows, driven by supernova explosions (Gressel et al. [16]) and cosmic rays (Hanasz et al. [17]). The mean-field dynamo in galaxy disks predicts that within a few $10^9\,\text{yr}$ large-scale regular fields are excited from the seed fields (Arshakian et al. [1]), forming patterns (“modes”) with different azimuthal symmetries in the disk and vertical symmetries in the halo.
3. Observation of galactic magnetism

Most of what we know about galactic magnetic fields comes through the detection of radio waves. The intensity of synchrotron emission is a measure of the number density of cosmic-ray electrons and of the strength of the total magnetic field component in the sky plane. The assumption of energy equipartition between the total cosmic rays and total magnetic fields allows us to calculate the total magnetic field strength from the synchrotron intensity (Beck & Krause [6]).

Polarized emission originates from ordered fields. As polarization “vectors” are ambiguous by 180°, they cannot distinguish regular (coherent) fields, defined to have a constant direction within the telescope beam, from anisotropic fields, which are generated from turbulent fields by compressing or shearing gas flows, so that their direction frequently reverses perpendicular to the flow direction. Unpolarized synchrotron emission indicates turbulent fields which have random directions.

The intrinsic degree of linear polarization of synchrotron emission is about 75%. The observed degree of polarization is smaller due to the contribution of unpolarized thermal emission, by Faraday depolarization along the line of sight and across the beam (Sokoloff et al. [26]) and by geometrical depolarization due to variations of the field orientation within the beam.

At radio wavelengths of a few centimeters and below, the orientation of the observed B-vector is parallel to the field orientation, so that the magnetic patterns of many galaxies can be mapped directly (e.g. Beck [4]). At longer wavelengths, the observed polarization vector is rotated in a magnetized thermal plasma by Faraday rotation. The rotation angle increases with the square of the wavelength λ² and with the Rotation Measure (RM), which is the integral of the plasma density and the strength of the component of the field along the line of sight. As the rotation angle is sensitive to the sign of the field direction, only regular fields give rise to Faraday rotation, while anisotropic and random fields do not.

4. Magnetic fields in barred galaxies

The gravitational potential of strongly barred galaxies drives noncircular orbits and gas inflow. In many barred galaxies a circumnuclear ring is formed. Numerical models show that gas streamlines are deflected in the bar region along shock fronts, behind which the cold gas is compressed in a fast shearing flow (Athanassoula [2]). The compression regions traced by massive dust lanes develop along the edge of the bar that is leading with respect to the galaxy’s rotation because the gas rotates faster than the bar pattern.

20 galaxies with large bars were observed with the Very Large Array (VLA) and with the Australia Telescope Compact Array (ATCA) (Beck et al. [8, 9]). The total radio luminosity (a measure of the total magnetic field strength) is strongest in galaxies with high far-infrared luminosity (indicating high star-formation activity), a result similar to that in non-barred galaxies. The average radio intensity, radio luminosity and star-formation activity all correlate with the relative bar length. Polarized emission was detected in 17 of the 20 barred galaxies.

NGC 1097 (Fig. 1) is one of the nearest barred galaxies and hosts a huge bar of about 16 kpc length. The total and polarized radio intensities are strongest in the downstream region of the dust lanes (southeast of the center) by compression of turbulent fields in the bar’s shock. The pattern of field lines in NGC 1097 is similar to that of the gas streamlines as obtained in numerical simulations (Athanassoula [2]). This suggests that the ordered magnetic field is aligned with the flow and amplified by shear. Remarkably, the optical image of NGC 1097 shows dust filaments in the upstream region which are aligned with the ordered field (Fig. 1). Between the region upstream of the southern bar and the downstream region the field lines smoothly change their orientation by almost 90°. The ordered field is also hardly compressed, probably coupled to the diffuse gas and strong enough to affect its flow (Beck et al. [9]). The polarization pattern in barred galaxies can be used as a tracer of shearing gas flows in the sky plane and complements spectroscopic measurements of radial velocities.
5. Magnetic fields in circumnuclear rings and gas inflows

Barred galaxies can create a gas reservoir and starburst in the central kiloparsec, fuelling an AGN needs other processes (e.g. Davies et al. [13]). The central regions of barred galaxies are often sites of ongoing intense star formation and strong magnetic fields. Bright radio emission has been observed in several galaxies with the following equipartition strengths of the total magnetic fields (Beck et al. [10]):

- NGC 1097: $\simeq 50\,\mu G$ in the circumnuclear ring, $50\,\mu G$ in the ring knots
- NGC 1365: $\simeq 60\,\mu G$ in the dust lanes (no ring)
- NGC 1672: $\simeq 70\,\mu G$ in the ring knots
- NGC 7552: $\simeq 105\,\mu G$ in the ring

Note that these values are lower limits because the energy densities of cosmic-ray protons and electrons in starburst regions are reduced by various losses (Thompson et al. [27]). This is supported by an investigation of the $\gamma$-ray and radio emission from the starburst galaxies M 82 and NGC 253 which suggests that most of the radio emission is from secondaries undergoing strong bremsstrahlung and ionization losses (Lacki et al. [20]).

One of the key problems of AGN physics is how to fuel the nucleus with gas from the central region, which needs outwards transport of angular momentum (Davies et al. [12]). Magnetic fields can help here. The circumnuclear ring of NGC 1097 is bright in the optical, IR and radio spectral ranges. It has a diameter of about 1.5 kpc and an active nucleus in its center (Fig. 2). The nonthermal and weakly polarized radio emission is a signature of strong turbulent magnetic
fields (Beck et al. [9]). Magnetic stress in the differentially rotating circumnuclear ring can drive mass inflow (Balbus & Hawley [3]) at a rate of:

$$\frac{dM}{dt} = 2\pi \sigma T_{r\phi} / \Omega$$  \hspace{1cm} (1)$$

where $\sigma$ is the surface mass density, $\Omega$ its angular rotation velocity and $T_{r\phi}$ is the magnetic stress tensor. $r$ and $\phi$ denote the radial and azimuthal field components. Its dominant component can be written in terms of the Alfvén velocity $v_A$ as $T_{r\phi} \approx - < v_{A,r} v_{A,\phi} >$. This yields:

$$\frac{dM}{dt} = - ( < b_r b_\phi > + B_r B_\phi ) h / \Omega$$  \hspace{1cm} (2)$$

where $h$ is the scale height of the gas, $b$ the strength of the turbulent field and $B$ that of the ordered field. The correlation between $b_r$ and $b_\phi$ is generated by shear from differential rotation. For NGC 1097, $h \approx 100$ pc, $v \approx 450$ km/s at 1 kpc radius, $b_r \approx b_\phi \approx 50 \mu$G and $B_r \approx B_\phi \approx 10 \mu$G give an inflow rate of several $M_\odot$/yr, which is sufficient to fuel the activity of the nucleus of this galaxy (Beck et al. [9]). This mechanism can be expected to operate in many galaxies.

Equi-partition between the energy densities of cosmic rays and magnetic fields yields:

$$\frac{dM}{dt} \approx -B_{tot}^2 h / \Omega \propto -I_{sync}^{0.5} h / \Omega \propto -I_{IR}^{0.5} h / \Omega \propto -SFR^{0.5} h / \Omega$$  \hspace{1cm} (3)$$

where $B_{tot}$ is the total field strength, $I_{sync}$ is the radio synchrotron intensity which is proportional to the infrared intensity $I_{IR}$ (the radio-infrared correlation) and hence to the star-formation rate $SFR$. The relation between the bolometric luminosity of AGNs $L_{bol}$ and the $SFR$ of their hosts (e.g. Trakhtenbrot & Netzer [28]) can be explained by this scenario. The relation between the accretion rate and $SFR$ (Eq. 3) should be tested with a sample of galaxies.

The ordered field in the ring of NGC 1097 has a spiral pattern and extends towards the nucleus. Its pitch angle agrees with that of the spiral filaments seen in dust and H$_2$ (Prieto et al. [22], Davies et al. [12]), suggesting gas inflow along the magnetic field lines.

Radio emission is a tracer of star formation also in distant galaxies. The radio-infrared correlation holds to redshifts of at least $z \approx 3$ (Murphy [21]), indicating strong magnetic fields in young galaxies, probably generated by the turbulent dynamo mechanism (Schleicher et al. [24]). Infrared observations indicate that star formation in the hosts of the most luminous AGNs peaked at $z \approx 3$ and decreased at later epochs (Serjeant et al. [25]), which is consistent with the evolution of the accretion rate onto supermassive black holes (Trakhtenbrot et al. [29]). The strong magnetic fields in young galaxies may serve as the link between star formation and accretion.

6. The nuclear outflow of the starburst galaxy NGC 253

NGC 253 is a prototypical starburst galaxy, hosting a starburst nucleus (Brunthaler et al. [11]). Its high inclination of 78.5° allows observing the extraplanar emission. The bright radio halo (Fig. 3) is probably a result of a galactic wind with a speed of about 300 km/s (Heesen et al. [18]).

Radio observations of the inner starburst region with high resolution revealed four filaments with widths of less than 40 pc and lengths of at least 500 pc (Fig. 4). These are interpreted as the boundaries of the outflow cone of hot gas interacting with the halo gas (Heesen et al. [19]). The equipartition strength of the total field in the filaments is at least 40 $\mu$G, that in the central region $\geq 160$ $\mu$G.

Faraday rotation measures (RM) between 3 cm and 6 cm wavelengths are consistent with an axisymmetric, even-parity, spiral magnetic field in the disk at radii of more than 2 kpc, while
Figure 3. Total radio emission (contours and colors) and polarization $B$–vectors of the spiral galaxy NGC 253, combined from observations at 6 cm wavelength with the VLA and the Effelsberg telescope and smoothed to 30" resolution (Heesen et al. [18]).

Figure 4. Total radio emission (grayscale) of the inner starburst region of NGC 253, observed at 20 cm with the VLA at a resolution of 1.3" x 2.2" (Heesen et al. [19]). The radio filaments (F1–4) and the minimum (M1) are indicated. The contours show the 12CO(2–1) emission, observed with the SMA (Sakamoto et al. [23]).

Figure 5. Total radio emission (contours) of the inner starburst region of the galaxy NGC 253, observed at 20 cm wavelength with the VLA at a resolution of 1.3" x 2.2" (Heesen et al. [19]). The colour image shows the X-ray emission (0.5-5 keV) measured with the CHANDRA satellite.

Figure 6. Model of the helical magnetic field in the walls of the outflow cone (Heesen et al. [19]).

the field in the inner disk is anisotropic (Heesen et al. [19]). Near the SE minor axis, in the region of the X-ray outflow cone (Fig. 5), RM jumps between $+300 \text{ rad m}^{-2}$ and $-300 \text{ rad m}^{-2}$. This is interpreted as the Faraday rotation of the polarized emission from the background disk.
by the helical field in the walls of the outflow extending to at least 1.2 kpc from the center (Fig. 6). Only the inner part of this helical field structure is seen in emission (Fig. 4). The northern outflow cone is located behind the disk, so that its X-ray emission is mostly absorbed and cannot Faraday-rotate the radio emission.

The galaxy NGC 3079 hosts an energetic wind-driven outflow which extends 3 kpc above and below the plane (Duric & Seaquist [14]) and emits strong and highly polarized synchrotron emission, in contrast to NGC 253. Radio-bright nuclear outflows seem to be rare.

7. Summary and outlook
Magnetic fields in the central regions of galaxies are dynamically important. Magnetic stress drives gas inflow from the circumnuclear regions towards the nuclei. This process connects the star formation activity to the accretion rate and could be important for the formation of supermassive black holes. Ordered fields as observed by polarized radio emission may trace the direction of gas in- and outflows.

Results have been obtained so far only for radio-bright and nearby galaxies. A better insight into the interaction between gas and magnetic fields, especially near galactic nuclei, needs higher resolution and higher sensitivity. The EVLA has largely improved the sensitivity for radio continuum observations. The EVLA project CHANGES (PI: Judith Irwin) will search for outflows in a large sample of edge-on galaxies. The goal for the next decade is the Square Kilometre Array (SKA) with a collecting area of about 100x that of present-day telescopes. The SKA will open a new era in the observation of cosmic magnetic fields (Beck [5]). Starburst galaxies will be observable out to redshifts of $z \simeq 3$ (Murphy [21]).

8. References
[1] Arshakian T G, Beck R, Krause M and Sokoloff D 2009 A&A 494 21
[2] Athanassoula E 1992 MNRAS 259 345
[3] Balbus S A and Hawley J F 1998 Rev. Mod. Phys. 70 1
[4] Beck R 2005 Cosmic Magnetic Fields ed R Wielebinski and R Beck (Berlin: Springer) p 41
[5] Beck R 2010 PoS(ISKAF2010)003
[6] Beck R and Krause M 2005 Astron. Nachr. 326 414
[7] Beck R, Brandenburg A, Moss D, Shukurov A and Sokoloff D 1996 Ann. Rev. A&A 34 155
[8] Beck R, Shoutenkov V, Ehle M, et al 2002 A&A 391 83
[9] Beck R, Fletcher A, Shukurov A, et al 2005 A&A 444 739
[10] Beck R, Ehle M, Fletcher A, et al 2005b The Evolution of Starbursts ed S Hüttemeister et al AIP Conf. Proc. 783 216
[11] Brunthaler A, Castangia P, Tarchi A, et al 2009 A&A 497 103
[12] Davies R I, Maciejewski W, Hicks E K S, et al 2009 ApJ 702 114
[13] Davies R I, Hicks E, Schartmann M, et al 2010 Co-Evolution of Central Black Holes and Galaxies ed B M Peterson et al (Cambridge: Cambridge University Press) p 283
[14] Duric N and Seaquist E R 1988 ApJ 326 574
[15] Fletcher A, Berkhuizen E M, Beck R and Shukurov A 2004 A&A 414 53
[16] Gressel O, Elstner D, Ziegler U and Rüdiger G 2008 A&A 486 L35
[17] Hanasz M, Wótański D and Kowalik K 2009 ApJ 706 L155
[18] Heesen V, Beck R, Krause M and Dettmar R-J 2009 A&A 494 563
[19] Heesen V, Beck R, Krause M and Dettmar R-J 2011 A&A 535 A79
[20] Lacki B C, Thompson T A, Quataert E, Loeb A and Waxman E 2011 ApJ 734:107
[21] Murphy E 2009 ApJ 706 482
[22] Prieto M A, Maciejewski W and Reunanen J 2005 AJ 130 1472
[23] Sakamoto K, Ho P T P, Iono D, et al 2006 ApJ 636 685
[24] Schleicher D R G, Banerjee R, Sur S, et al 2010 A&A 522 A115
[25] Serjeant S, Bertoldi F, Blain A W, et al 2010 A&A 518 L7
[26] Sokoloff D D, Bykov A A, Shukurov A, et al 1998 MNRAS 299 189 and MNRAS 303 207
[27] Thompson T A, Quataert E, Waxman E, Murray N and Martin C L 2006 ApJ 645 186
[28] Trakhtenbrot B and Netzer H 2010 MNRAS 406 L35
[29] Trakhtenbrot B, Netzer H, Lira P and Shemmer O 2011 ApJ 730:7