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Magnetic Fields Around Galactic Discs

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Abstract: Magnetic fields in the discs of spiral galaxies are quite well understood, although, of course, many details still require investigation and future observations with new generations of radio telescopes will be valuable here. Magnetic configurations around galactic discs and, in particular, the magnetic field components perpendicular to galactic discs seem to be much more poorly understood and deserve further investigation both observationally and by modelling. Another problem to be addressed in future investigations is the magnetic configuration in galactic halos and, in particular, interactions with the intergalactic medium and various winds. Finally, the importance of the observational determination of such drivers of galactic dynamo action as mirror asymmetry of the turbulent galactic flows are briefly discussed.

Keywords: magnetic fields; galactic dynamo; galactic halos

1. Introduction

Magnetic fields in the discs of spiral galaxies are quite well understood and have been studied from both observational and theoretical viewpoints (see, e.g., [1]). Of course, many details still deserve investigation and future observations with new generations of radio telescopes will be very relevant here (see contribution of Chamandy and Beck to this volume). In particular, observational identification of evolutionary effects continue to present a desirable goal (e.g., [2,3]).

The topic of magnetic configurations around galactic discs seems to be much more poorly understood and deserves further investigation, both observationally and by modelling. Here, we present our vision of some specific problems.

Conventional models for galactic dynamos have concentrated their efforts on magnetic field components parallel to the galactic equatorial plane. The governing equations have often been formulated to give results that are presented in terms of integral quantities calculated perpendicular to galactic discs. This is what is found directly from observations.

The point however is that magnetic fields perpendicular to the galactic equatorial plane are both interesting and important; however, contemporary studies have addressed these much less than fields parallel to the equatorial plane. We discuss possible future progress in this direction in Sections 2 and 3.

Another problem (Section 4) under discussion is the magnetic configuration in galactic halos. It is clear that the halo medium is also magnetised, however we know much less about magnetic field configurations in halos than in discs. In particular, it is quite unclear what happens at the outer boundary of galactic halos, and in particular how this can be determined. Are there similarities to the magnetosphere of the Earth? How much magnetic flux penetrates from the galactic halo into the surrounding space, and how important is it for intergalactic and intracluster magnetism?

Related points for discussion are the possible coexistence and interaction of magnetic fields in a galactic halo with a galactic wind, and the effects of galactic motion through the intergalactic medium. These are discussed in Section 5.

Finally, we consider perspectives for the observational determination of drivers of galactic dynamo action. The best determined quantity driving galactic dynamo action appears to be the galactic differential rotation (of course, there are unresolved issues here as everywhere). In contrast, what is believed to be the other important driver, namely mirror asymmetry of turbulent galactic flows, remains almost not tackled observationally (Section 6).

2. The Magnetic Field Perpendicular to the Galactic Disc

Conventional galactic dynamo models start from the mean-field dynamo equation

$$\frac{\partial \mathbf{B}}{\partial t} = \mathrm{curl}\, \mathbf{v} \times \mathbf{B} + \mathrm{curl}\, \alpha \mathbf{B} + \eta \Delta \mathbf{B}, \tag{1}$$

where $\mathbf{B}$ is the mean magnetic field, η is the turbulent diffusivity and the term α is known as the α-effect, which describes the mirror asymmetry of turbulent motions. This equation is supplemented by the solenoidality condition

$$\mathrm{div}\, \mathbf{B} = 0. \tag{2}$$

Equation (2) follows from Equation (1) after some algebra, provided that the seed field is solenoidal. In other words, we have four dependent equations for three magnetic field components, say, B_r, B_ϕ and B_z (r, ϕ and z are cylindrical coordinates and the z-axis is perpendicular to the galactic plane). There is sufficient freedom available to describe a range of problems.

The first mean-field dynamo models for spiral galaxies (e.g., [4]) exploited implicitly the point that B_z is expected to be much smaller than $B_\perp$, the projection of $\mathbf{B}$ on the equatorial plane of the galaxy. Indeed, estimating derivatives in Equation (2) by algebraic ratios, we get an estimate

$$\frac{B_\perp}{r} + \frac{B_z}{h} = 0, \tag{3}$$

yielding $B_z \sim h/r B_\perp$ (here, r is galactic radius and h is the thickness of the galactic disc). Because h/r is quite small, $B_z \ll B_\perp$ while $B_\perp$ is substantial in the disc and may also be so in the halo. An explicit construction of $B_z(r, \phi, z)$ where ϕ is the azimuthal coordinate is given in [5]. Note that near the centre of the disc where h/r is not small, the approximation fails and results may be unreliable.

Observationally, little is known about regular fields B_z, see [6] and references therein concerning the first observational evidence of regular halo fields with scales exceeding 800 pc and that may reach several kpc. Regular fields are of large scale without reversals. The vertical fields observed in the halos of edge-on galaxies could be stretched field loops or anisotropic turbulent fields. However, Pakmor et al. [7] argued that the 1–2 kpc scale polarised structures observed, e.g., in M51 and NGC628, are not due to expanding HI shells or Parker loops. Rotation measures (RMs) in edge-on galaxies are small, corresponding to the small line of sight components of integrated regular fields. In mildly inclined face-on galaxies (such as NGC6946 and M51), the RM patterns are mostly due to disc fields, however a halo contribution may be recognisable as well. A detailed discussion for M51 is given in [8]. In the almost perfectly face-on galaxy NGC628 [9], RM patterns on scales of 1–2 kpc are seen, possibly from vertical halo fields. The various data available for M51 (e.g., [10]) also indicate patterns of substantial vertical halo fields on scales of 1–2 kpc. However, no vertical fields clearly related to dynamo action in the disc have been identified so far. Perhaps, this can be considered as observational support for the theoretical estimate presented above; however, further clarification is desirable.

A natural step is to solve at the first stage the two equations for B_r and B_ϕ, which follow from Equation (1), and then to restore B_z from Equation (2) [4]. The assumption of small B_z can be justified a posteriori. The magnetic field projection $B_\perp = (B_r, B_\phi, 0)$ by definition does not contain B_z (cf., however, the work of Nixon et al. [11] who in turn referred to the work of Henriksen and Irwin [12] who discussed the first stage of the procedure only). However, B_z arises from Equation (2) at the next stage. In particular, a complicated shape for an individual magnetic line, which rotates many times in the galactic disc around the galactic centre and then leaves the disc to perform a complicated walk in its surroundings, is reconstructed in [13].

Summarising, we emphasise that the initial procedure suggested in [4] does contain a vertical magnetic component B_z, coming from Equation (2)[1]. However, this procedure is quite lengthy and has been substantially simplified and reformulated in terms of observable quantities, i.e., integrals of B_r and B_ϕ taken in the vertical direction across the disc. This is the no-z model (see above as well as, e.g., [14] and the tuning in [15]). Note that it implicitly assumes even parity of the global field with respect to the galactic mid-plane. In the framework of the no-z model, the vertical field B_z is again obtained from the solenoidality condition in Equation (2). See also the discussion in [16].

In the spirit of the above approaches, reconstruction of the vertical magnetic field component begins at the equatorial plane. If the point of interest is magnetic field behaviour at large z, where the thin disc approximation does not apply, a different approach to the mean-field equations is required. In particular, axisymmetry and solenoidality of the field can be used to reduce the problem to a system of two variables, e.g., A_ϕ and B_ϕ as functions of r, ϕ and z, and thus to two equations that can be solved by various numerical methods (**A** is the vector potential for the field). In particular, many papers (e.g., [17–19]) discuss axisymmetric magnetic field structure in the disc and the galactic halo ("embedded disc" models), and thus determine the vertical magnetic field component as well as the component parallel to the galactic disc.

Modelling of a global non-axisymmetric magnetic field is a trickier, but still feasible, business (e.g., [5]). The field obtained by such modelling certainly contains a non-vanishing vertical component.

In all these models solenoidality of the dynamo excited magnetic field is provided by the form of the mean-field dynamo equations, being conserved by the numerical and analytical methods of solution. There are now a number of large-scale numerical simulations (DNS) for parts of, or even entire, galaxies, although computational limitations mean that they have not been as fully explored as the computationally much simpler mean-field models. It seems that mean-field models, maybe with some calibration from selected DNS, are likely to remain important in making wider surveys of parameter space and rapid testing of new ideas.

In any case, the mean-field dynamo equations predict that the magnetic field generated in the galactic disc is expected to be symmetric with respect to the galactic equator (i.e., of even parity). As the galactic disc is quite thin, this point looks quite natural and usually is accepted as obvious. Excitation of an odd mode is in principle also possible, but requires much stronger dynamo action than to excite the symmetric mode. It is unclear whether such a mode could persist in the nonlinear regime—specific numerical exploration would be needed—but note again that the no-z approximation explicitly assumes that fields are of even parity. On the other hand, the galactic halo is quasi-spherical and excitation of an odd mode here also looks possible. Magnetic fields generated in the halo can penetrate into the disc and vice versa. Conditions for coexistence of odd and even dynamo generated magnetic modes is far from being straightforward and one dynamo can enslave the other [20][2].

Observational verification of the true magnetic field symmetry of galactic discs and halos is an important goal. The point here is that traditional narrow-bandwidth radio polarisation observations of magnetic fields in discs of external face-on galaxies give integral quantities taken in the direction perpendicular to the galactic plane and it is not easy to separate the two types of symmetry based on such data. Observations of edge-on galaxies are suitable mainly for understanding magnetic field

1 Indeed, $B_z = 0$ and $\mathrm{div}\,\mathbf{B} = 0$ in axisymmetric disc dynamo models gives a physically infeasible situation, see Section 3.
2 The problem is relevant for stellar dynamos as well (e.g., [21]).

configurations in galactic halos. However, if the resolution is high enough these can be used to test the symmetry of the disc field (even or odd) as well.

As we are living inside the Milky Way, the contributions of the northern and southern galactic hemispheres to the Faraday rotation are well separated here, and the Milky Way could be expected to be an instructive example to determine the symmetry of galactic magnetic fields with respect to the equatorial plane. The point however is that the magnetic field in the solar vicinity in the North Galactic Hemisphere is strongly perturbed by the North Polar Spur, which makes the determination of magnetic field symmetry problematic (e.g., [22], see also [7], showing that the kind of large-scale RM symmetry found strongly depends on location within the Milky Way.)

It looks plausible that the methods of Faraday tomography [23] using wide-band radio polarisation data applied to the multi-wavelength observations of external galaxies can contribute to the determination of the magnetic field symmetry for external galaxies. The Faraday dispersion measure, expected from a line of sight observation taken transverse to the galactic disc when the magnetic field is of even parity with respect to the central plane, can be expected to give features in the Faraday spectrum $F(\psi)$, where ψ is Faraday rotation. If the magnetic field is of even parity with respect to the galactic plane, this will correspond to the contribution of the magnetic layer near to the galactic equator. In contrast, a magnetic configuration with odd parity with respect to the galactic equator is expected to give two features $F(\pm\psi)$ where ψ is associated with the magnetic field in one hemisphere. Of course, $F(\psi)$ is affected by various other depolarisation effects that makes its shape much more complicated. However, the point appears to be an important one for future observations. This asymmetry only occurs at long wavelengths, where Faraday depolarisation destroys the polarised emission from the far-side halo.

Another observational tool is the asymmetry in polarised intensity along the major axis of mildly inclined galaxies (see [24,25]), which seems to support the even symmetry of halo fields.

3. A Note on Some Recent Papers

We note that much of the accepted modelling of the generation of disc fields has been challenged recently by Nixon et al. [11], who invoked the effect of differential rotation on a relic primordial magnetic field to generate toroidal field, without explicitly relying on dynamo action. We do not provide a detailed analysis/criticism of this paper, but only note what we feel to be some unsatisfactory features. In particular, Nixon et al. [11] asserted that mean field disc models do not allow description of a vertical field component. The above discussion shows this statement to be misconceived. In fact, using cylindrical coordinates for axisymmetric fields, we obtain from the solenoidality condition div $\mathbf{B} = 0$ that if $B_z = 0$, then $\partial(rB_r)/\partial r = 0$, and thus $B_r = f(z)/r$, thus giving a singularity on the axis! Nixon et al. [11] invoked several papers by Henriksen and collaborators (e.g., [12]). These papers make the mathematically convenient but physically non-motivated assumption that all quantities are functions of $\zeta = z/r$ only. In places, non-solenoidal fields are mentioned, and figure captions refer to non-null poloidal field lines in an axisymmetric model that cross the axis of symmetry. Small $|\zeta|$ is assumed, but halo fields are discussed. Diffusivity is ignored, but we note also that it is known that dynamos need small, but finite, magnetic diffusivity to work. Thus, we find their analysis to be at least difficult to interpret.

The basic ideas proposed by Nixon et al. [11], in which fields are essentially "relic" fields, modified by differential rotation, were discussed several decades ago. Nixon et al. [11] claimed a very long timescale for diffusion across the disc in the vertical direction, thus avoiding difficulties from field pinching. Thus, the current vertical field is essentially a distortion of the original "seed" field. In such a scenario, the winding-up timescale would be much longer than the rotation timescale, which is impossible for a frozen-in magnetic field. This long timescale is disputed, and in the absence of dynamo action the differential rotation winds up the magnetic field in the disc (the "winding problem"). There is also a "parity problem": it is hard to see how an initial, necessarily, odd parity fossil B_z can be converted into an even parity contemporary galactic field.

If the vertical diffusion time is as short as conventionally estimated, then without maintenance by dynamo action, large scale fields would be rapidly lost from the disc. This "relic field" concept was addressed at length in [4], see also [26][3].

The effects of an initial (seed) field generated by a small-scale dynamo and of near the equipartition strength compared to the kinetic energy of the energy of turbulent motions have been neglected—this is true of many studies of galactic dynamos. One important effect is a much shorter time for the mean-field dynamo to saturate. Even less studied are the consequences of the "continual seed" supplied by the coexistence of large- and small-scale dynamos (see, e.g., [28,29]).

Of course, there remain correlations that are expected theoretically but are not yet obtained observationally (e.g., [30,31]) and vice versa. However, this situation is not unusual for galactic studies (e.g., the contribution of Chamandy and Beck to this volume).

4. Magnetic Fields in Galactic Halos

Polarised emission from galactic halos that suggests the existence of large-scale magnetic fields in halos has been known for several decades (e.g., [1]). Recently, this expectation has been supported by significant RM observations (see [6]). In some sense, modelling of dynamos in galactic halos is based on the same ideas as for those in galactic discs. Indeed, differential rotation and mirror asymmetric turbulence seem to be inevitable in halos as well as in discs. Of course, we know much more about properties of the interstellar medium in discs than in halos, thus various estimates for dynamo drivers for halos are expected to be much more uncertain than those for the discs. Numerics for dynamo models in halos have some specific features that have been able to be modelled by modern computers for a considerable time. As a result, various specific models for magnetic field generation in halos have been suggested (e.g., [32,33]).

The point however is that the interstellar medium in halos (as well as in discs) is very inhomogeneous and is sometimes referred to as being multiphase. In particular, various outflows from the galactic disc into the halo and, possibly, from the halo into the surrounding intragalactic space, are observable (e.g., [34]).

There is convincing evidence (see discussion in [35]) for fast galactic winds with velocities of $U \sim$ 200–400 km/s. If these are included in the mean-field dynamo equations in a straightforward way as regular velocities, then such a wind would evacuate magnetic field from the halo and plausibly also from the disc, and destroy dynamo action and dynamo generated magnetic configurations (e.g., [35,36]). The point is that only a very small part of the interstellar mass may be involved in the wind motion. A possible approach here is to consider impulses rather than velocities, i.e., to say that an inhomogeneous wind with velocity U and corresponding density ρ_U can be replaced by a regular motion with vertical velocity V which can be found from the relation

$$V\rho = U\rho_U, \tag{4}$$

where $\rho > \rho_U$ is the mean density of the medium. In other words $V = Uf$ where f is the volume feeling factor of the wind. This approach is used in [33] and seems to give reasonable results. Effects of any inflow from the inter-galactic medium of returning fountain flows have not been modelled. The question of whether halo fields can be strong enough to influence flows remains open.

Of course, this device is only an auxiliary step and a more or less consistent mean-field description for a dynamo in a multiphase medium is very desirable. Even a formulation of basic approaches to the point would be highly welcome for the understanding of magnetic field generation in galactic halos. We note that the problem is important for magnetic field generation in the disc as well.

[3] For historical reasons, we also mention here [27].

Furthermore, the magnetic field seems to reverse frequently in halos due, e.g., to field loops, which may explain why we do not see a clear vertical symmetry of magnetic field when integrating over the whole galaxy. This may be consistent with the concept of magnetic fountain flows, as modelled in [37]. In any case, a mean-field approach here looks likely to be inadequate and an explicit representation of small-scale magnetic fields and the small-scale dynamo is required. Some preliminary steps in this direction are made in [38] for dwarf galaxies.

Taken together, we can say that the magnetic field structure in halos just above galactic discs is becoming more or less understood and is now ready for further investigations. What is much less clear is what happens at the outer boundary of galactic halos. In particular, is this boundary a well-defined concept or is there a smooth transition from galactic halos to intergalactic space? The second option looks more attractive because intergalactic space is something more than just a vacuum and motion of a galaxy through the intergalactic medium should be associated with some effects similar to those at the boundary of the Earth's magnetosphere. The analogy is obviously very crude, and observational and theoretical investigations look essential. A point to be clarified is whether there are winds from galactic halos into intergalactic space and how much magnetic flux is transported to outside of the halos. The point is important in particular in connection with the problem of the origins of magnetic fields in intra-cluster space. How much magnetic field can there be associated with galactic winds that transport magnetic field away from halos (cf. [39])?

5. Effects of Galactic Motion Through the Intergalactic Medium and Dynamo Action

Galaxies move through the intergalactic medium and this motion can affect gas in galaxies, galactic hydrodynamics and galactic magnetic fields. It is natural to expect that the effects are more pronounced in galaxies belonging to clusters. In particular, clear cases of the interaction between a galactic wind and the intra-cluster medium in the galaxy NGC 4388 are presented in [40]. This problem has attracted some attention (e.g., [41,42]).

The problem of the interaction of galactic magnetic fields with the intra-cluster medium is to some extent similar to the classical problem of interaction between the Earth's magnetic field and the solar wind, which leads to the development of the Earth's magnetosphere. Understandably, modelling of galactic magnetospheres is not directly analogous to modelling the Earth's magnetosphere. One point to be discussed here is that magnetic fields in galactic discs are assumed to have quadrupolar symmetry while the Earth's magnetic field is dipolar. General properties of magnetospheres of celestial bodies with quadrupolar magnetic fields still need to be understood, and the problem can be important for some stars where magnetic fields with quadrupolar symmetry are expected from stellar dynamo studies (e.g., [43]).

The main novelty of the problem is however that the motion of galaxies through the intra-cluster medium can affect the galactic interstellar medium. In contrast, the solar wind can hardly affect the motions in the liquid outer part of the Earth's core where the geodynamo is active. As a result, when modelling the Earth's magnetosphere, the Earth's magnetic field can be considered as prescribed. The same assumption has been made in the simplest models of galactic magnetospheres. In fact, the external flows associated with galactic motion through the intra-cluster medium can penetrate to the interior of galaxies and so affect internal dynamo action. As a result, instead of prescribing the magnetic field, it is better to consider dynamo generated galactic magnetic fields where the dynamo governing parameters are affected by the galactic motion through an external medium. A pilot research in this direction presented in [44] demonstrates that the effects of such a system can be quite pronounced and rather unexpected (an example of such an unexpected magnetic configuration is given in Figure 1). In particular, galactic tails can be substantially asymmetric with respect to the galactic motion. The point needs modelling of more realistic and complicated cases but looks both interesting and promising.

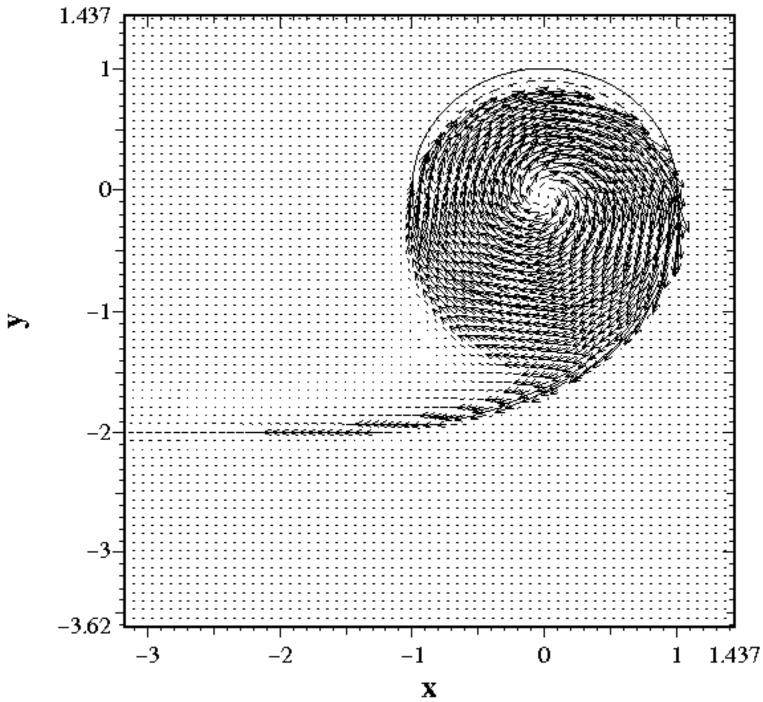

Figure 1. An example of a rather unexpected magnetic configuration produced by dynamo action (axisymmetric within the circle $x^2 + y^2 < 1$, which is shown) and a streaming velocity in the negative x-direction. This figure appeared in [44] where more examples can be found. The figure is reproduced by permission of A&A.

6. Quantifying Dynamo Drivers

The galactic mean-field dynamo is based on the joint action of two drivers, i.e., differential rotation and mirror asymmetry of interstellar turbulence. If we know anything for certain about spiral galactic hydrodynamics, it is galactic rotation curves, i.e., differential rotation. The situation with other drivers represented in the mean-field equations, such as the α-effect, is dramatically different. The degree of mirror asymmetry as quantified by helicity is a quantity that is quite difficult to determine by laboratory measurements, and of course even more so from astronomical observations. The point is that a direct measurement of the helicity of the vortex lines, known as hydrodynamic helicity, requires measurement of three velocity components as well as their derivatives. The traditional tool for making velocity measurements in astronomy is the Doppler effect, which gives the line-of-sight velocity component only. This is a more general problem which arises in comparing the results of dynamo modelling with observations for various celestial bodies.

At the moment, solar astronomy has had the most success towards solving this problem. This has been achieved as follows. The starting point is that there are two factors that contribute to the mirror asymmetry of magnetised flows, i.e., the velocity field represented by hydrodynamic helicity and the mirror asymmetry of the magnetic field, represented by magnetic line linkage, i.e., magnetic helicity, or a related quantity known as current helicity. The determination of magnetic field mirror asymmetry also requires knowledge of three magnetic field components. The solar magnetic field can be measured by the Zeeman effect, which can give all three magnetic field components. Seehafer [45] recognised that current helicity is the most accessible quantity for observational determination and suggested that this should be the first milestone, even if it is not the most attractive from a theoretical viewpoint. The suggestion has been generally accepted. Observational interpretation can be found in, e.g., [46]. Later methods for the observational identification of magnetic helicity [47], hydrodynamic helicity [48] and even their joint contribution to the α-effect [49,50] have been suggested. There are many remaining problems, however the direction of development is clear.

Similar developments in the field of galactic dynamo studies provide an obvious challenge for observers as well as for theoreticians. An important point is that galaxies are more or less transparent and it is possible to perform observations within the region of dynamo action, while solar observations are only possible at the solar surface and in the solar atmosphere, while the solar dynamo acts within the solar interior.

An obvious obstacle here is that the main tool to observe galactic magnetic fields is Faraday rotation. This gives the line of sight magnetic field component only. The degree of polarisation for radio continuum depends however on all three magnetic field components. This dependency provides the possibility of looking for various correlations in quantities that are associated with the degree of polarisation and are sensitive to mirror asymmetry. A correlation of this type is suggested in [51,52]. In 2018, West (see [53]) reported observational identification of such an effect in Milky Way observations. Bearing in mind the wisdom that even a ten thousand li journey begins with the first step, we hope that it is a first step on this promising yet difficult road.

In principle, it should be possible to estimate helicity from large-scale numerical simulations. However, existing attempts using box model (e.g., [54]) have been rather inconclusive, and there are many uncertainties in the models.

7. Conclusions

We have presented our view of how we might develop our understanding of the nature of magnetic fields in spiral galaxies. Of course, traditional statements of the problems still contain many points that deserve further clarification. The point however is that new interesting and important problems continue to appear. We hope that the younger generation of radioastronomers and MHD modellers will address the problems summarised above.

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