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Summary of the Discussions

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A major aim of the organisers was to stimulate debate, and thus substantial time was set aside for discussion. The following account does no more than recapitulate some of the more outstanding points raised. Apologies are offered to those whose contributions have been omitted because of the space limitations.

Introducing the discussion following the talks by P. P. Kronberg, Å. Nordlund & Ö. Rögnvaldsson and J. M. Stone, on the theme of *"Extragalactic and pregalactic magnetic fields"*, the session moderator K. Subramanian (Pune, India) identified five particular, somewhat interrelated, outstanding topics: (1) the nature and parameters of magnetic fields at extragalactic scales from galaxy clusters to cosmological distances and (2) at large redshifts; (3) the origin of seed fields for the galactic dynamo; (4) the rôle of magnetic fields in cosmological structure formation; and (5) the origin of the fields observed in galaxy clusters.

Kronberg pointed out that AGN jets of Mpc scales and winds from young starburst galaxies may contaminate the intergalactic space with magnetic fields, which can provide seeds for galactic dynamos. The highest redshift at which a μG-strength magnetic field of galactic scale has been firmly detected is an absorption system at $z = 1.95$ seen in the spectrum of a jet quasar 3C191. Quasi-uniform magnetic fields at cosmological scales seem to be constrained at a level below about 10^{-11} G by Faraday rotation measurements. Subramanian quoted unpublished work with S. M. Chitre & D. Narasimha on Faraday rotation differences between distinct images of a gravitationally lensed object at high redshift. The twin quasar 0957+561 shows a difference of $100\,\mathrm{rad\,m^{-2}}$, possibly indicative of a large-scale field in the lens.

A. Shukurov asked whether constraints on the seed fields produced by plasma expansion from jets and AGNs, with a frozen-in magnetic field, will be prohibitive because of the strong difference between plasma densities within and outside the AGNs. In reply, A. Brandenburg and T. Enßlin (Garching, Germany) pointed out that this constraint can be relaxed because of the continuous supply of magnetic field by extragalactic jets throughout their lifetimes. Brandenburg argued that this can result in an rms field of order 1 μG in a volume of 1 Mpc^3. Enßlin suggested a more modest estimate of the resulting magnetic energy of 10^{66} erg Gpc^{-3} corresponding to a rms field of 0.03 μG over a Gpc scale, whilst stressing both the likely inhomogeneity of the field and uncertainty of the estimate.

L. Mestel (Sussex, UK) remarked that although magnetic fields can assist star formation through efficient angular momentum transport, and may also bias the initial mass function towards more massive stars, it is probably premature to claim that a magnetic field at large z is essential for the first stars to form.

E. M. Berkhuijsen (Bonn, Germany) moderated the session with talks by R. Beck, M. J. Reid, R. Wielebinski et al. and K. T. Chyży on the topic *"Observations of Galactic Magnetic Fields"*. Much of the discussion centred on the magnetic reversals observed in the Milky Way (at least one or two reversals are inferred from extragalactic and pulsar RMs), but apparently not in the majority of nearby galaxies (except for M51 and NGC 2997). A reversal at a 10 kpc scale has been possibly detected in the jet quasar PKS 1229-02 (Kronberg). Subramanian stressed the importance of the scale of the reversals; any on a scale of 100 pc or so can be attributed naturally to the tangled small-scale component of the magnetic field, whereas reversals on significantly larger scales require a specific explanation.

Beck said that field reversals in external galaxies on scales less than a few kpc are difficult to observe. Shukurov pointed out that the region(s) with reversed field in the Milky Way can be restricted not only in radius but also in azimuth, similarly to what has been inferred for the disc of M51. J. L. Han (Beijing, China) noted that new pulsar RMs in the fourth Galactic quadrant seem to indicate that the reversal extends over a wide range of azimuth between the Sagittarius and Orion arms, but Shukurov stressed that it would be difficult to prove that this range extends over the whole circle. Nordlund said that large-scale reversals confined to a thin galactic disc would be difficult to observe in an external galaxy, but Beck asked why such reversals would not extend further from the disc plane. Brandenburg commented that MHD simulations suggested that the poloidal field was likely to be less coherent than the toroidal (azimuthal) component, since the large-scale toroidal field is much stronger than the poloidal because of the differential rotation, and so the relative fluctuations (caused by the small-scale field component) are stronger in the poloidal field. P. Katgert (Leiden, The Netherlands) mentioned that WRST polarization maps near 90 cm and the Canadian Galactic Plane survey near 20 cm wavelengths show RM reversals on smaller scales down to a fraction of a parsec; this indicates that magnetic fields at small scales can be significantly stronger than the large-scale field (further evidence is discussed by R. Wielebinski in this Proceedings).

Berkhuijsen drew attention to the fact that in normal spiral galaxies the magnetic field and density wave structures have the same pitch angles, indicative of a direct interaction, whereas in barred galaxies the velocity and magnetic fields are parallel in, but not upstream of, the bar. There is a need for detailed high-resolution comparisons of magnetic field structures and non-circular velocity fields, and to understand the coupling between them. Further, detailed knowledge of the properties of turbulent fields, both in the Milky Way and external galaxies, is lacking, but could yield valuable information.

When introducing the discussion after the talks by D. Moss, M. Rees, D. Elstner and A. Shukurov on the topic *"Galactic Hydrodynamics"*, the moderator, P. P. Kronberg (Toronto, Canada) observed that, although dynamo models are now producing more realistic models of galactic magnetic fields, a number of problems remain. Can dynamo theory explain field reversals as discussed above, and why does the Milky Way appear to be so special in this respect? Are the reversals stable over galactic lifetimes, or just transient phenomena? Progress would be assisted by Faraday rotation measurements of galactic discs, to see how far above and below the discs the magnetic structure retains its coherence. RM probes of M31 and other galaxies could also lead to clarification. New observations of Zeeman splitting of OH maser lines (Reid, this Proceedings) may provide an additional probe on smaller scales.

Turning to the rather puzzling observations of strong, ordered fields observed in dwarf galaxies, which rotate only slowly (and so have little or no alpha effect), Kronberg suggested that such fields might have been amplified by a fast dynamo associated with shearing instabilities in gas outflows. On the 'seed field problem', he commented that evidence is now accumulating that magnetic fields could already be approaching microgauss strength at early stages of galaxy formation, perhaps originating from starbursts, galactic black holes or individual stars. Interstellar magnetic fields therefore seem likely to have been a significant component of the ISM since primeval galaxy times. This could significantly affect our ideas about how galactic dynamos work.

Nordlund asked whether large-scale galactic dynamo action was necessary to generate the large-scale fields – could velocity fields associated with AGNs and galaxy clusters, followed by the processes involved in galaxy formation (including differential rotation) amplify a weak pre-existing magnetic field to the strength and form currently observed? He said that, unless seed fields were in excess of about 10^{-10} G, mean field dynamos did not have enough time to generate microgauss fields as observed in certain galaxies at $z = 2$ or 3. Brandenburg replied that small-scale dynamos, with growth times of order 10^7 yr, could rapidly generate microgauss-strength, small-scale fields, which could then be organised by mean field dynamo action over larger scales.

Moss, Shukurov and Beck were doubtful whether any theory relying on amplification and rotational distortion of a 'primeval' field without any genuine dynamo action could give fields of the commonly observed geometry (predominantly axisymmetric and quadrupole-like). Nordlund replied that with suitable initial conditions, largely axisymmetric fields with predominantly even symmetry in the disc plane could result; departure from these symmetries would only be visible higher in the halo region.

Beck reminded the meeting of the important observation that the regular magnetic field in spiral galaxies appeared strongest between the spiral arms. New, or modified, models of the interaction between the gas density wave and the dynamo are required to explain this phenomenon.

Turning to magnetic fields in elliptical galaxies, M. Rees (Cambridge, UK) asked whether any dynamo action was needed, if elliptical galaxies were formed by mergers of spirals – couldn't the fields seen in elliptical galaxies result from those present in the parent spiral galaxies? Shukurov responded that, given the highly disturbed state of the ISM after a collision, in the absence of further dynamo action, magnetic energy would be transferred to small scales and eventually be lost as heat.

M. Melek (Cairo, Egypt) asked about the rôle, persistence and strength of primordial seed fields. Rees replied there are good reasons to think that stars could generate the required seed fields. Most primordial seed field models encounter difficulties, for example fields generated near the QCD phase transition time in an inflationary universe model would now have very small scales.

The final session on *"Turbulent magnetic fields, turbulent diffusion and difficulties of dynamo theory"* consisted of the papers of F. Cattaneo et al., E. G. Blackman & G. B. Field, K. Subramanian and A. Brandenburg, and was moderated by D. D. Sokoloff (Moscow, Russia). The fundamental issue was whether the dynamical feedback of small-scale magnetic fields on the turbulence can suppress dynamo action before the large-scale fields can grow to physically important strengths, i.e., close to equipartition with turbulent kinetic energy.

Shukurov asked whether this problem is unique to galactic dynamos. Should it not also occur in the Sun, where we are reasonably confident that dynamo action does occur? N. O. Weiss (Cambridge, UK) replied that in the Sun, unlike galaxies, the strong toroidal magnetic field is thought to be confined to the tachocline, and the alpha effect operates in the overlying convection zone, where the field is relatively weak. Brandenburg recalled that the helicity constraint is quite general and insensitive to the spatial distribution of the induction effects. He also pointed out that this constraint limits the growth of the large-scale field, but possibly not strongly the cycle period, because the sign of the magnetic helicity remains the same from one cycle to the next.

Blackman stressed that 3D MHD simulations show that magnetic energy accumulates at the outer turbulent scale rather than at the smallest scales. This seems to be in contrast with models resulting in catastrophic alpha quenching. He also pointed out that the effects of (uncertain) boundary conditions may be crucial – galactic dynamos require a flux of mean field through the boundary, and allowing a similar flux of magnetic helicity in MHD simulations may negate the strong alpha quenching results. Weiss commented that the physical mechanism underlying any such flux needs elucidation. D. W. Hughes (Leeds, UK) said that, if the results on catastrophic alpha quenching are to be seriously challenged, a physical mechanism affecting the picture selectively at high Reynolds numbers should be proposed. Subramanian mentioned the possible rôle of reconnection in removing magnetic helicity at small scales, and Hughes linked the catastrophic alpha quenching with the suppression of Lagrangian chaos in the fluid motions by equipartition-strength magnetic fields at the smallest scales (see Cattaneo et al., this Proceedings).

In conclusion, Sokoloff emphasized the necessity of relating more closely the MHD models to real astronomical objects. Quantitative theoretical predictions on the properties of small-scale fields need to be compared with high-quality observations in terms of such statistical characteristics as correlation functions. An outstanding problem is to obtain estimates of the mean helicity of interstellar turbulence from observations of gas motions.

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