

## The Origin and Cosmogonic Implications of Seed Magnetic Fields

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### SUMMARY

Cosmic magnetic fields may owe their present strength to dynamo amplification, but to initiate this process a seed field is required. This seed field may be primordial, or else (more likely) a consequence of battery mechanisms in protogalaxies or in the first stars. The way it actually originated would have determined the nature of the intergalactic field, and the epoch when this field arose: this in turn would have controlled thermal conductivity and related diffusion effects in the intergalactic medium. Although magnetic effects probably influence the formation of stars at the present epoch, this may not have been so for the first stellar generation; the initial mass function and the star formation efficiency may, for this reason alone, have been very different at early eras of galactic history.

### 1 INTRODUCTION

Cosmic magnetic fields are ubiquitous within our own and other galaxies, they are essential for the process of synchrotron radiation and may be strong enough for magnetic stresses to be dynamically important; even a very weak field can inhibit thermal conductivity and associated diffusion processes. The issue of how magnetic fields originate and evolve is therefore of interest in many astrophysical contexts, particularly for cosmogony. A field which is initially very weak (and dynamically trivial) can be amplified by a dynamo mechanism in a medium with large-scale internal motions – this can happen within galactic discs, inside individual stars, and in other contexts (e.g. accretion flows). For exhaustive expositions of these processes, see Moffatt (1978) or Parker (1979). But all discussions of dynamo effects invoke a so-called seed field: a non-zero field must be there already, otherwise a dynamo process has nothing to feed on. Because subsequent amplification can be exponential, the seed can be very weak if many  $e$ -folding times are available. The presence of an adequate seed field is, in many theoretical discussions, just ‘taken for granted’. Several alternative origins for it have been suggested, but little attention seems to have been given to deciding among the options. This question is relevant to placing dynamo theories in their proper astrophysical context. But it is of broader interest because (as I shall discuss) the various alternatives have interesting implications for star formation and galactic evolution.

Early work on cosmic magnetism pre-dated any real knowledge of the large-scale fields that pervade the interstellar medium: it was therefore natural to focus on stellar fields, and seek an internal origin for them. Biermann (1950) discovered that a battery process could create a field *ab initio* in

rotating stars. Pressure gradients, acting on the electrons, generate a poloidal current, which builds up slowly at a rate limited by the 'back emf'. Mestel and others subsequently showed that this battery would be 'shorted out' through back-reaction on the rotation field which is responsible for the Biermann e.m.f. while the field was still far weaker than actual stellar fields (see Mestel & Roxburgh 1962; Mestel 1965; Roxburgh 1966); the battery can be more readily maintained within a star after nuclear burning has established a molecular weight gradient (Mestel & Moss 1983). Biermann's battery might nevertheless be effective enough to generate the seed for a stellar dynamo.

There is no mystery about where the initial field came from in recently formed stars, or even in the Sun (which was born rather late in Galactic history): such stars presumably condensed from interstellar matter pervaded, like the presently-observed interstellar medium, by a pre-existing large-scale galactic field. During the earlier stages of protostellar collapse, magnetic effects would influence the fragmentation process (modifying the Jeans mass, etc.) and magnetic torques could extract angular momentum (Mestel & Paris 1979, 1984). The likely flux through a protostellar cloud is, indeed, far larger than can be squeezed into a star. As the density rises during protostellar collapse, the rise in magnetic field strength depends on whether collapse occurs along or across the field. However, the fragments would have a flux/mass ratio close to the virial limit, thus implying much stronger fields than are observed even in magnetic stars. Flux must therefore be lost in the later stages of a protostar's collapse. The leakage could occur via ambipolar diffusion, when the free electron density has fallen to a very low value, in the manner first described by Mestel & Spitzer (1956); alternatively, flux could be lost via anomalous resistivity or buoyancy effects.

Just as a protostar would start off with too much frozen-in-flux, its angular momentum is initially also excessive. Flux leakage must occur at some stage, but the longer it is delayed, the greater is the effectiveness of the  $B$ -field in removing or redistributing angular momentum. [Mestel (1986) gives a comprehensive review of how magnetic fields might affect star formation.] Once a star has settled down on the main sequence, dynamo mechanisms sustain the field and are responsible for the magnetic activity and variability observed in the Sun.

The magnetic field in a differentially rotating galactic-disc could itself have been amplified by dynamo action. The winding-up of a frozen-in field leads just to linear growth (i.e. an amplification proportional to the number of revolutions); but a dynamo, which involves radial motions, can lead to exponential growth on a timescale of order the galactic rotational period. Given that our galaxy, and other disc systems, may have undergone  $\gtrsim 50$  revolutions, there seems no fundamental problem in generating the field from a seed weaker by many powers of ten – this is the assumption made by, for instance, Zel'dovich, Ruzmaikin & Sokoloff (1983). But the origin of the galactic seed field still poses a genuine problem: a galactic-scale field even as weak as  $10^{-20}$  G needs some physical explanation. [The loosely-wound bi-symmetric structure of galactic fields may imply that the dynamo amplification of a particular mode of the initial seed field with this symmetry was triggered; but some authors appear to be sceptical of the efficiency of

dynamo amplification (Sofue, Fujimoto & Wielebinski 1986), suggesting instead that galaxies may have formed with dynamically-significant fields (e.g. Sawa & Fujimoto 1980). This alternative viewpoint, which has not yet been developed in great detail, would place more stringent demands on field-generation processes that were primordial, or at least pregalactic.]

The purpose of this paper is to air several inter-related issues relating to cosmic magnetic fields which seem to have received rather little attention in the literature:

- (i) Where did the seed fields in *galaxies* come from, and how strong were they?
- (ii) Is intergalactic space pervaded by a magnetic field, and what are its effects?
- (iii) What difference would it make to, for instance, star formation if there were no magnetic field (or if the field were dynamically negligible), as might be expected early in the history of a galaxy?

## 2 THE SEED FIELD IN PROTOGALAXIES

### 2.1 *Cosmological origin*

Cosmologists have sometimes speculated that the Universe formed with an initial magnetic field. If this field were homogeneous, it would induce an overall cosmic anisotropy (e.g. Melvin 1964; Thorne 1967; Jacobs 1969); any such field is constrained by the lack of a quadrupole anisotropy in the background, and by cosmic nucleosynthesis, but these considerations cannot exclude the kind of very weak field that might act as a seed for subsequent amplification. In the context of recent ideas on symmetry-breaking, it has been conjectured that magnetic fields might arise spontaneously at an ultra-early epoch. These would not necessarily be uniform throughout its entire presently-observed Universe, but might at least have a 'macroscopic' characteristic scale. Such fields could be cosmogonically important if the Universe contained a network of superconducting strings (Ostriker, Thomson & Witten 1986).

To have a direct effect on triggering galaxy formation (see Rees 1971; Wasserman 1978), magnetic stresses must be at least comparable with the post-recombination gas pressure: this requires a field that would (adiabatically expanded to the present epoch) amount to  $10^{-9}$  G. On the other hand, a fossil universal field that was far too weak to affect gas-dynamical processes could cause the gyroradius to be smaller than the collisional mean free-path of ions in a protogalaxy or protocluster, and thereby inhibit thermal conductivity, sedimentation of heavier species, etc (see section 3). A still weaker field that affected neither the behaviour of pregalactic gas nor the local physics at early epochs (e.g. nucleosynthesis) might none the less suffice to initiate a dynamo: a seed field of  $\sim 10^{-20}$  G could grow to the present Galactic strength of a few times  $10^{-6}$  G provided that the  $e$ -folding time were no more than a few times  $10^8$  years (comparable with the galactic rotation period); but in a young disc galaxy, magnetic fields would not have had time to grow to a dynamically-significant level.

## 2.2 Pregalactic origin

Harrison (1970) suggested an interesting possibility whereby a cosmic battery could operate before the (re)combination epoch, creating a weak field even if none were present in the very early universe. His proposed mechanism required a *non-zero vorticity* in the primordial perturbations. The photons of the background thermal radiation would be strongly coupled to the electrons via Thomson scattering, but less strongly coupled to the ions. Angular momentum conservation in the photon-electron component (for which rest mass is unimportant, so that  $\rho \propto R^{-4}$ ) implies that the angular velocity of a comoving eddy falls off as  $R^{-1}$  during the expansion ( $R$  being the cosmological scale factor); angular velocities in the ion component (where rest mass dominates, and  $\rho \propto R^{-3}$ ) would, if it moved independently of the other components, go as  $R^{-2}$ . This difference tends to build up a current in each eddy; the back-emf would couple the two components so that everything spun down at some compromise rate, the current (and associated field) growing at the slow rate permitted by Faraday's law. On galactic scales, the build-up is so slow that the resultant fields would be only  $\sim 10^{-18}$  G; these might never the less be adequate seeds for a subsequent dynamo. This is the proposed mechanism for cosmic pregalactic magnetic fields that can most readily be quantified.

## 2.3 Protogalactic origin

Harrison's scheme, as he formulated it, depended on the presence of primordial vorticity or 'whirls' (see Ozernoi, 1978 and earlier references cited therein). But this idea has lost favour with most cosmologists, primarily because 'whirls' decay during the cosmic expansion, whereas irrotational density perturbations (arising from initial curvature fluctuations) would grow: the initial conditions required in order that rotational perturbations are still significant in the post-recombination universe seem rather implausible. If the initial fluctuations were irrotational, vorticity generation would have to await the development of the first non-linearities (such as would naturally arise via oblique shocks, tidal interaction of neighbouring perturbations which subsequently collapse, etc.). After protogalaxies have collapsed and matter has been reionized, a current could build up because Compton drag on the microwave background applies a torque tending to brake the rotation of the 'electron fluid', without there being a corresponding drag on the ions. This is analogous to Harrison's scheme, although it results from the angular velocity of the electron fluid being slightly *lower* (rather than higher) than that of the ions. Mishustin & Ruzmaikin (1972) estimate that a galactic seed field of  $10^{-21}$  G could thereby arise. Though even feebler than the pregalactic field that would arise from primordial vorticity, this may nevertheless be enough to initiate dynamo amplification.

If the initial cosmological fluctuations were non-Gaussian (as, for instance, would be those induced by cosmic strings) then non-linear phenomena could be initiated, even before recombination, in localized regions (e.g. in shocks or vortices in the wakes of fast-moving strings, or in accretion flows onto slow-moving closed loops). Were the strings superconducting (Witten 1985), their

motions might in principle lead to dynamo amplification, but this idea has yet to be seriously explored. (G.Field, private communication).

#### 2.4 *Origin in the very first stars*

The formation of an adequate seed galactic field may alternatively have had to await the onset of star formation. Even if the very first stars formed from material with zero flux, a field could be generated within each by a combination of battery and dynamo mechanisms. (Stellar lifetimes exceed the dynamical timescales, by many powers of ten, so there is here much less problem in 'getting things started' than for the galactic field.) This field could be injected into the interstellar medium via stellar winds, or by stars which end their lives via supernovae.

Could the entire galactic field have been seeded in this way by just a few stars? Let us take the Crab Nebula as an illustration: its entire field, of strength  $\sim 10^{-4}$  G and pervading a volume of several cubic parsecs, could have been built up during the lifetime of the precursor star and then expelled via a relativistic wind (Kardashev 1965; Rees & Gunn 1974). Even though the *net* flux is small, the sign of flux is uniform within quadrants, so the field is ordered on a scale of 1 pc. The field in the Crab Nebula comes from a relativistic wind 'spun off' the central rotating neutron star. The  $\sim 10^{12}$  G fields in neutron stars could themselves be adiabatically-compressed fossils of the weaker but more extensive fields in the precursor main-sequence stars. Alternatively, as suggested by Urpin & Yakovlev (1980a, b) and Blandford, Applegate & Hernquist (1983), fields could be built up in neutron stars, or regenerated in old neutron stars after any fossil field had decayed, by a battery mechanism analogous to that originally discussed by Biermann. Because neutron stars have a solid crust, the 'shorting out' cannot quench the process as it does in ordinary stars.

Even the flux from just one star, if it were able to spread sufficiently rapidly, could pervade the whole galaxy with a field exceeding that generated, according to Mishustin & Ruzmaikin (1972), via the Compton drag in a protogalaxy. But this is an unrealistic scenario: we would expect that huge numbers of stars would form in a protogalaxy, within a single stellar-evolutionary timescale, once the process gets started. The mean field strength that could permeate the galaxy would be commensurately larger than that from a single star. But then another question arises: is it possible to generate a flux distribution ordered over a 1 kpc scale, as our Galactic field is known to be from studies of Faraday rotation? The contributions from many different stars would be randomly aligned; the resultant large-scale flux would therefore grow only as the square root of the number of stars, and be swamped by a smaller-scale component with many reversals. However, the predominant present-day field could have acquired a large-scale structure provided that only the large-scale component underwent dynamo amplification. (For reviews see Parker 1979 and Zweibel 1986).

## 2.5 *Origin in active galactic nuclei*

The magnetic fields that play a crucial role in active galactic nuclei could be advected inward from the body of the host galaxy by an accretion flow. Moreover, even if the infalling matter were unmagnetized, accretion flows offer promising sites for field generation and amplification (e.g. Bisnovatyi-Kogan & Ruzmaikin 1976; Pudritz 1981). Whatever the origin of the magnetic fields in galactic nuclei, the outflows associated with non-thermal activity around a collapsed object can transport plasma and associated flux into the surrounding volume. In particular, jet-like collimated ejection can inflate the components of giant radio sources, pervaded (like a scaled-up version of the interior of the Crab Nebula) by magnetic flux. If the flows in jets were precisely laminar, and the velocities were constant across the entire cross-section, then the resultant fields would be essentially transverse; however, velocity gradients and shear layers can regenerate a longitudinal component. The observed polarization of extended radio sources suggests that the field is indeed stretched by shearing motions. [In a short paper predating the work just mentioned, Hoyle (1969) suggested that massive spinning objects in galactic nuclei were responsible for building up large-scale galactic fields.]

## 3 THE INTERGALACTIC MAGNETIC FIELD: POSSIBLE IMPLICATIONS FOR GAS IN CLUSTERS AND INTERGALACTIC CLOUDS

Magnetic fields are not dynamically important unless their associated stresses are comparable with gas pressure. Rough observational constraints on large scale intergalactic fields come from the lack of any  $z$ -dependence in the Faraday rotation measure of distant radio sources, apart from effects attributable to intervening galaxies (Kronberg & Perry 1982), implying that any cumulative effect arising from propagation through the intergalactic medium is swamped by the effects of our Galaxy and the source itself (Brecher & Blumenthal 1970; Rees & Reinhardt 1972). These limits are  $7 \times 10^{-8} (L/5 \text{ Mpc})^{-1/2} \Omega_g^{-1} \text{ G}$ , for a field correlated on a scale  $L$ , and where the gas contributes a fraction  $\Omega_g$  of the critical density. This limit is good enough to constrain the dynamical importance of intergalactic fields. But even a much weaker magnetic field can inhibit diffusion processes; significant effects require only that the field be strong enough to bring the gyroradius ( $\propto B^{-1} T^{1/2}$  for  $kT < m_e c^2$ ) below the Coulomb collision length ( $\propto n^{-1} T^2$ ), and a field  $\sim 10^{-14} \text{ G}$  is more than enough to do this within a hot diffuse plasma on the scale of galaxies and clusters. It is therefore interesting to know whether even a very weak all-pervasive field exists, and at what stage it might have originated.

There are two reasons for expecting there now to be a widespread magnetic field in the intergalactic medium. Cosmic radio sources, and their faded remnants, must pervade a large fraction of intergalactic space. The cumulative effect of all generations of radio sources – adiabatically expanding, fading, and eventually merging – would build up an intergalactic field. We do not know how many generations of radio sources there may have been. An upper limit can be set by noting that the relativistic electrons would eventually deposit the bulk of their energy via inverse Compton scattering of the

microwave background, and the resultant radiation cannot exceed the observed X-ray background (Rees & Setti, 1968). If the typical radio sources were to generate comparable amounts of energy in the forms of magnetic fields and Gev electrons (which are affected by adiabatic expansion in a similar fashion), the resultant field could be as high as  $10^{-8}$  G; this could, however, be a substantial overestimate. The true value is at least as uncertain as the contribution made by AGNs to the intergalactic cosmic ray flux. A second reason is that interstellar gas from individual galaxies could have been expelled via supernova-driven winds, or 'swept' by ram pressure from fast-moving galaxies within clusters.

The intergalactic magnetic flux arising in these two ways would not of course contribute an overall ordered cosmic field; the scale of its reversals would be comparable with the separation of galaxies. Within the uncertainties, we can merely say that, while the present intergalactic field is unlikely to impact significantly on large scale dynamics, it is almost certainly strong enough to affect diffusion processes – and, in particular, to bring the thermal conductivity below the standard 'Spitzer' value. One cannot quantify this without knowing the field configuration; however, the fact that large diffuse radio sources can trap relativistic electrons, and indeed often have sharp boundaries, tells us that even Gev particles cannot travel freely, and therefore that the magnetic field configuration must surely inhibit the thermal conductivity of the thermal plasma.

Diffusion effects are unlikely to be important now, at least on scales of clusters of galaxies (or larger), because the cumulative influence of ejecta from individual galaxies would have created an all-pervasive field. This has an important effect on, for instance, the thermal balance of the gas within clusters where cooling and inflow occurs (see Fabian, Nulsen & Canizares 1984 for a review). If the conductivity were as high as the 'Spitzer' value, then heat would be transferred inward, destroying the observed temperature gradient.

The properties of the clouds responsible for Lyman line absorption in quasar spectra could be influenced by weak magnetic fields. If these clouds are in pressure balance with a much hotter intercloud medium, then thermal conductivity sets a lower limit to the cloud sizes (Sargent *et al.* 1980). If conductivity were inhibited across the field but not along it, then clouds developing via thermal instability would tend to be filamentary or sheet-like, elongated along the field direction. Suppression of conductivity would allow very thin clouds to survive.

There is certainly no direct evidence as to whether or not any such fields existed when the galaxies first formed (at an epoch  $z = 5$ ), before the advent of most strong radio sources. Unless there were a cosmological field of primordial origin (as discussed in sections 2.1 and 2.2), gaseous protogalaxies and protoclusters would be free of magnetic fields at the time of their formation. Particle diffusion would then be inhibited only by Coulomb collisions, and thermal conductivity would be high. Sedimentation of heavy ions (Fabian & Pringle 1977; Rephaeli 1978), and of deuterium relative to hydrogen (Gil'fanov & Sunyaev 1984), could have occurred at that epoch even if these processes are suppressed at more recent epochs.

#### 4 COSMOGONIC IMPLICATIONS OF GALACTIC (OR PREGALACTIC) FIELDS: MODIFICATIONS OF THE INITIAL MASS FUNCTION

In a galaxy like our own, the large-scale field has now built up to a strength that is dynamically important: magnetic stresses can react back on the flow, magnetic bubbles can escape from the disc, etc. It then stabilizes at an 'equipartition' level; indeed the only reason the 'equipartition' assumption ever yields a sensible estimate of any cosmic magnetic field is that there are many situations when a system has survived for so many '*e*-folding' time-scales that the field would be limited only by a dynamical back-reaction. This presumably took less than 100 galactic rotations, since our Galaxy has not undergone more than this; on the other hand, the build-up of the field must have had to await several exponentiations of a weak seed.

Irrespective of exactly when the galactic seed field originated, we would be surprised if magnetic stresses were as dynamically important in a young galaxy as they now are in the interstellar medium.

One of the stumbling-blocks confronting attempts to model galactic evolution quantitatively is our ignorance of how star formation works. We understand neither the efficiency (i.e. the fraction of the mass in a collapsing cloud that condenses into stars on a dynamical timescale) nor what determines the mass spectrum of the stars that do form – the 'initial mass function', or IMF. Chemical composition is surely important: heavy elements dominate the cooling and opacity at temperatures below  $10^4$  K. Most authors who have addressed the issue have therefore speculated that the first stars (the so-called population III, and extreme population II) may have a different IMF if for no other reason than that they form from H and He uncontaminated by heavy elements. No one is sure what effect this has on the IMF, but there would certainly be a consensus that it must have *some* effect.

But perhaps another environmental difference between the most ancient sites of star formation and present interstellar clouds is equally important: the lack (in the former) of a dynamically significant magnetic field. This would seem to offer at least as plausible a reason as the lack of heavy elements for expecting the first stars to have a different IMF. The actual effect of heavy elements on the IMF is unclear: the lack of coolants raises the Jeans mass at a given density, but the associated absence of opacity allows a fragmenting cloud to achieve higher densities before the opacity becomes important enough to trap radiation and inhibit cooling. These two effects act in opposite directions; and it is in any case unclear to what extent the characteristic masses of stars actually relate to the Jeans mass.

The net effect of magnetic fields on present-day star formation is even less clear: they raise the effective Jeans mass, but transport away angular momentum (Mestel & Paris 1979, 1984). The strength of the interstellar field also controls the properties of interstellar clouds, i.e. how they fragment, and whether they coalesce or 'bounce' when they collide (Clifford 1986). If magnetic fields were the only effective agent for removing angular momentum, then star formation could not proceed at all without them. This was the viewpoint taken by Bisnovatyi-Kogan, Ruzmaikin & Sunyaev (1973), who proposed that Jeans instability in young galaxies gave rise to rotationally-supported clouds. A battery mechanism within each such cloud, fol-

lowed by dynamo action, generated a magnetic field; and only then could the first stars form. But if, contrariwise, turbulent viscosity and gravitational effects, acting unassisted by magnetic torques, were effective enough to enable protostars to resolve their 'angular momentum problem' (Larson 1984) then the first magnetic fields would emanate from the first stars (bypassing the field-generation in clouds postulated by Bisnovatyi-Kogan *et al.* 1973). Once dynamically-significant fields became widespread, they might modify the process of collapse and fragmentation.

A supernova explosion into a medium where there was initially no magnetic field would be interestingly different from a present-day supernova (R.J.Tayler, private communication). Fast-moving chemically-enriched ejecta would penetrate more readily into the external medium, and might even escape the galaxy completely, because of the long effective mean free-path; on the other hand, the lack of a thin collisionless shock front would preclude acceleration of cosmic rays by mechanisms that depend on repeated passages through the shock front.

Star formation is still so poorly understood that firm claims are premature. But perhaps theorists concerned with early star formation and galactic evolution should be as attentive to environmental differences of a hydromagnetic kind as they have traditionally been to compositional differences.

The  $e$ -folding timescale for dynamo-type field amplification is related to the dynamical time. To build up a dynamically significant field in a self-gravitating system, the gas must persist for a number (perhaps  $> 10$ ) of free-fall times. This statement holds irrespective of whether the seed field comes from a pregalactic battery mechanism, or is generated within (and then expelled from) the very first stars. There has by now been plenty of time for the galactic field to build up in disc systems like our own galaxy. On the other hand, elliptical galaxies and the bulge and halo components of spirals are believed to consist of stars that formed during an initial collapse. One might therefore conjecture that, in so far as magnetic fields influence star formation, there would be one formation mode in old discs (i.e. those that have existed, differentially rotating, for many orbital periods) and another in young discs and in ellipticals. Stars formed via these two modes could differ in their IMF and in the fraction of binaries.

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#### REFERENCES

- Biermann, L., 1950. *Z. Naturf. A.*, **5**, 65.  
 Bisnovatyi-Kogan, G.S. & Ruzmaikin, A.A., 1976. *Astrophys. Space Sci.*, **42**, 401.  
 Bisnovatyi-Kogan, G.S., Ruzmaikin, A.A. & Sunyaev, R.A., 1973. *Soviet Astr.*, **17**, 137.  
 Blandford, R.D., Applegate, J.H. & Hernquist, L., 1983. *Mon. Not. R. astr. Soc.*, **204**, 1025.  
 Brecher, K. & Blumenthal, G., 1970. *Astrophys. Lett.*, **6**, 169.  
 Clifford, P., 1986. *Mon. Not. R. astr. Soc.*, **216**, 93.  
 Fabian, A.C. & Pringle, J.E., 1977. *Mon. Not. R. astr. Soc.*, **181**, 5P.  
 Fabian, A.C., Nulsen, P.E.J. & Canizares, C., 1984. *Nature*, **310**, 733.  
 Gil'fanov, M.R. & Sunyaev, R.A., 1984. *Soviet Astr. Lett.*, **10**, 137.  
 Harrison, E.R., 1970. *Mon. Not. R. astr. Soc.*, **147**, 279.  
 Hoyle, F., 1969. *Nature*, **223**, 936.  
 Jacobs, K., 1969. *Astrophys. J.*, **155**, 379.

- Kardashev, N.S., 1965. *Soviet Astr.-A.J.*, **8**, 643.
- Kronberg, P.P. & Perry, J.J., 1982. *Astrophys. J.*, **263**, 518.
- Larson, R.B., 1984. *Mon. Not. R. astr. Soc.*, **206**, 197.
- Melvin, M.A., 1964. *Phys. Lett.*, **8**, 65.
- Mestel, L., 1965. In *Stellar Structure*, p. 465, eds Aller, L.H. & McLaughlin, D.B. Chicago University Press.
- Mestel, L., 1986. *Physica Scripta*, **TII**, 53.
- Mestel, L. & Moss, D.L., 1983. *Mon. Not. R. astr. Soc.*, **204**, 557.
- Mestel, L. & Paris, R.B., 1979. *Mon. Not. R. astr. Soc.*, **187**, 337.
- Mestel, L. & Paris, R.B., 1984. *Astr. Astrophys.*, **136**, 98.
- Mestel, L. & Roxburgh, I.W., 1962. *Astrophys. J.*, **136**, 615.
- Mestel, L. & Spitzer, L., 1956. *Mon. Not. R. astr. Soc.*, **116**, 505.
- Mishustin, I.N. & Ruzmaikin, A.A., 1972. *Sov. Phys. JETP*, **34**, 233.
- Moffatt, H.K., 1978. *Magnetic Field Generation in Electrically Conducting Fluids*, Cambridge University Press.
- Ostriker, J.P., Thomson, C. & Witten, E., 1986. *Phys. Lett.* **180**, 231.
- Ozernoi, L.M., 1978. In *Large Scale Structure of the Universe*, p.427, eds, Longair, M.S. & Einasto, J., Reidel, Holland.
- Parker, E.N., 1979. *Cosmic Magnetic Fields*, Oxford University Press.
- Pudritz, R., 1981. *Mon. Not. R. astr. Soc.*, **195**, 881.
- Rephaeli, Y., 1978. *Astrophys. J.*, **225**, 335.
- Rees, M.J., 1971. In *General Relativity and Cosmology*, p. 315, ed. Sachs, R.K., Academic Press.
- Rees, M.J. & Gunn, J.E., 1974. *Mon. Not. R. astr. Soc.*, **167**, 1.
- Rees, M.J. & Setti, G., 1968. *Nature*, **219**, 127.
- Rees, M.J. & Reinhardt, M., 1972. *Astr. Astrophys.*, **19**, 189.
- Roxburgh, I.W., 1966. *Mon. Not. R. astr. Soc.*, **132**, 201.
- Sargent, W.L.W., Young, P.J., Boksenberg, A. & Tytler, D., 1980. *Astrophys. J. Suppl.*, **42**, 41.
- Sawa, T. & Fujimoto, M., 1980. *Proc. astr. Soc. Japan*, **32**, 551.
- Sofue, Y., Fujimoto, M. & Wielebinski, R., 1986. *Ann. Rev. Astr. Astrophys.*, **24**, 459.
- Thorne, K.S., 1967. *Astrophys. J.*, **148**, 51.
- Urpin, V.A. & Yakovlev, D.G., 1980a. *Soviet Astr.*, **24**, 126.
- Urpin, V.A. & Yakovlev, D.G., 1980b. *Soviet Astr.*, **24**, 425.
- Wasserman, I., 1978. *Astrophys. J.*, **224**, 337.
- Witten, E., 1985. *Nucl. Phys.*, **B249**, 557.
- Zel'dovich, Y.B., Ruzmaikin, A.A. & Sokoloff, D.D., 1983. *Magnetic Fields in Astrophysics*, Gordon & Breach.
- Zweibel, E.G., 1986. *Proc. Summer School 'Physical Processes in the Interstellar Medium'*, Grand Tetons, Wyoming.