ON THE ORIGIN OF THE GALACTIC MAGNETIC FIELD

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Abstract

The galactic magnetic field is commonly supposed to be due to a dynamo acting on some large scale seed field. A major difficulty with this idea is that estimates of reasonable seed field strengths tend to be quite low, on the order of $\sim 10^{-20}$ gauss. Here we examine the contribution due to the flux entrained in winds from protostars formed in the first dynamo e-folding time of a galaxy’s existence. Using a minimal estimate of a protostellar magnetic field we find that if each protostar ejects a single current ring, sufficient to maintain flux freezing in the wind, than the large scale average dipole field from all such current rings will be at least 5 orders of magnitude larger than previous seed field estimates. Allowing for a reasonable amount of magnetic activity in protostars during an extended period of mass loss increases this to a dipole seed field of $\sim 10^{-12}$ gauss. For the purposes of producing a seed field it is irrelevant whether or not this initial injection of flux takes place in a newly formed galactic disk, or in star forming proto-galactic clouds. The compression of this dipole field into a thin disk will lead to a large scale $B_r \sim 10^{-10.5}$ gauss. Initially, field strengths on smaller scales will be larger, but nowhere near current levels.
1. INTRODUCTION

The origin of galactic magnetic fields is a long standing problem in theoretical astrophysics. Virtually all spiral galaxies have magnetic fields of a few microgauss which are spatially coherent over several kiloparsecs. This implies that the average magnetic energy density is comparable to the average energy densities of cosmic rays and the interstellar medium, which in turn suggests that galactic magnetic fields reached a state of saturation some (unknown) time in the past. Since galaxies are so large, and their constituent gases are so highly conducting, the dissipative time scale for these fields is absurdly long. Either galactic magnetic fields are simply the visible manifestation of some pre-existing cosmological field (cf. Piddington 1972; Kulsrud 1990) or they are spectacular examples of fast dynamos, in which turbulent transport takes the place of ohmic dissipation (Parker 1971; Vainshtein and Ruzmaikin 1971, 1972). The notion that there exist large scale magnetic fields as a consequence of physical processes that occur in the very early universe has been explored by a number of authors (Vilenkin & Leahy 1982; Hogan 1983; Turner & Widrow 1988; Quashnock, Loeb & Spergel 1988; Vachaspati 1991; Ratra 1992; Dolgov & Silk 1992, Dolgov & Rhie 1992). The bulk of this work is neither clearly wrong, nor clearly right, inasmuch as it requires the invention of novel physical mechanisms for which no evidence can be found (aside from the existence of galactic magnetic fields themselves). A few, such as Quashnock et al. (1988), suggest mechanisms which may generate small scale fields, but which cannot, by themselves, give rise to large scale coherent fields. One of the earliest (Harrison 1970) pointed out that such fields would arise naturally from large scale rotational motions during the radiation epoch, but the existence of such motions are not easily reconciled with standard cosmological
models and constraints on their amplitude limit the resulting field to very low levels.

One is therefore tempted to search for the source of the field among physical processes that happen during, or after, the epoch of galaxy formation, when the relevant physics can be assumed to be testable, if not completely understood. In this picture one assumes that the galactic field grows from some small seed due to the action of an $\alpha - \Omega$ dynamo, i.e. a dynamo in which some small mean helicity generates a radial magnetic field, $B_r$, from an azimuthal one, $B_\theta$. Differential rotation in the galactic disk then closes the loop by generating $B_\theta$ from $B_r$. The growth rate is roughly $B_r/B_\theta \sim (\alpha_{\theta \theta} \Omega/H)^{1/2}$, where $\alpha_{\theta \theta}$ is the azimuthal component of the helicity tensor, $H$ is the disk scale height, and $\Omega$ is the disk rotation frequency (about $10^{-15}$ in the solar neighborhood). There is no general agreement on the source, or value, of $\alpha_{\theta \theta}$ but given the largely azimuthal nature of galactic magnetic fields it seems reasonable to assume that the dynamo growth rate ought to be $\sim 10^{-16}$ to within factors of order unity. Given a current field strength of $3 \times 10^{-6}$ gauss one finds that a seed field of $\sim 3 \times 10^{-19}$ gauss should be sufficient to produce the observed fields after 10 billion years (but see below!). Of course, the uncertainties in growth times and the ages of galactic disks enter into the exponent of this calculation, so the result cannot be taken too literally.

Can such a seed field be produced? One can, of course, return to the early universe as a source, with the advantage that one requires a much weaker cosmological effect, and therefore a much smaller modern intergalactic field, but the problem remains that such models are only loosely connected to testable physics. There are two proposals which involve the direct creation of a large scale galactic field using only standard physics, the microwave background compton drag on electrons in the galactic disk (Mishustin and Ruzmaikin 1971), and the thermoelectric effect (Biermann 1950; Roxburgh 1966; Lazarian 1992). The
former is due to the deceleration of the electrons in a rotating galactic disk due to their interaction with the microwave background. This creates a large scale dipole field at a rate of

$$\partial_t \vec{B} = \frac{m_p c}{e} \frac{\Omega}{\tau_e \gamma}$$  \hspace{1cm} (1)$$

$m_p$ is the proton mass, $c$ is the speed of light, $e$ is the charge of an electron, $\Omega$ is the rotation rate of the galaxy, and $\tau_e \gamma$ is the electron-photon coupling time. This field will begin to grow as soon as the protogalactic disk forms. Since $\tau_e \gamma \propto (1 + z)^{-4}$ we note that most of the field creation takes place shortly after galaxy formation. Plugging in a galactic rotation rate of $10^{-15}$, a galaxy formation epoch of $z = 5$ in a flat cosmological model, and a current background temperature of $2.75 \text{ K}$ we find a seed field of $1.6 \times 10^{-20} h^{-1} \text{ gauss}$, where $h$ is Hubble’s constant in units of $100 \text{ km/s/Mpc}$. This result scales with the redshift of galaxy formation as $(1 + z)^{5/2}$ and the value we have used is, if anything, a little high, so this mechanism would appear to be marginal at best.

The thermoelectric effect comes from a misalignment of temperature and density gradients in a gas, a circumstance that would naturally arise in a rotationally supported system. The field grows linearly in time, at a rate of

$$\partial_t \vec{B} \approx \frac{m_p c}{e} \frac{\vec{\nabla} P \times \vec{\nabla} \rho}{\rho^2}$$  \hspace{1cm} (2)$$

For a rotationally supported disk this is approximately

$$\partial_t \vec{B} \sim \frac{m_p c}{e} \frac{H}{r} \Omega^2$$  \hspace{1cm} (3)$$

where $H$ is the disk thickness and $r$ is the disk radius. We note that smaller systems have a tremendous advantage in generating magnetic fields in this way since $\Omega$ will scale as $H^{-1}$ for similar temperatures, a point previously stressed by Pudritz & Silk (1989). If we follow Lazarian (1992) and take a gas temperature of $10^6 \text{ K}$ in a disk with a radius of $10 \text{ Kpc}$ we find that this mechanism will produce
a galactic seed field of approximately $3 \times 10^{-19}$ gauss in $10^{16}$ seconds. This seems more promising, although still somewhat marginal, assuming a dynamo growth time comparable to the current age of our galaxy. (Lazarian quotes a value of $3 \times 10^{-17}$ gauss, but the discrepancy is due to an integration time of $10^9$ years and a vertical scale height for the hot gas of 100 pc. The former parameter corresponds to an integration time of at least 3 dynamo e-folding times, which seems unnecessary. The scale height is unrealistically small. We take $H \sim c_s/\Omega$.) However, such disagreements are unimportant. The real problem with this proposal has to do with the time required for the galactic dynamo to reach saturation.

Recent work on inferred magnetic field strengths for high redshift systems (Kronberg, & Perry 1982; Welter, Perry, & Kronberg 1984; Wolfe, Lanzetta, & Oren 1992) has dramatically shortened the time available for galactic dynamos to work. Kronberg and collaborators initially showed that observations of Faraday rotation measures of QSOs with, and without, metal line absorption systems, indicates that dynamically significant magnetic fields were already present at redshifts of a few. Since then Wolfe et al. showed that this effect was strongest for QSOs with Lyman limit systems, and that these systems, usually identified with early galactic disks, contain kiloparsec scale coherent magnetic fields with strengths of a few microgauss at redshifts of about 2. The strength and scale of these fields are indistinguishable from the fields of galaxies today, indicating that galactic dynamos reach saturation in a short time, not much more than a billion years. Assuming that galactic dynamos grow at less than the galactic rotation rate (typically about $10^{-15}$ s$^{-1}$) this implies a total amplification less than about $10^{19.5}$. More realistic galactic dynamos, with growth rates of $\sim 10^{-16}$, cannot possibly amplify a seed field of $\sim 10^{-20}$ gauss to saturation in such a
short time. This has led to a renewed interest in the early universe as a site for seed field generation.

Is it really necessary to resort to such speculative processes? Here we will argue that the process of star formation itself will inevitably lead to a significant galactic seed field, one that is larger than that contributed by any but the most ad hoc cosmological processes. We start by considering current observations of very young stellar objects. It is well known that such objects appear to drive very strong molecular outflows and that such outflows accompany the formation of comparatively low mass stars (for a general review see Fukui et al. 1992 and references contained therein). These outflows are broad (length-to-width ratios of 3 to 1 appear to be typical), large (with typical dimensions of \( \sim 10^{18} \) cm) and dense (with typical densities of about \( 10^3 \) \( cm^{-3} \)). In addition to these broad outflows, protostars have associated optical jets, on scales of \( \sim 10^{17} \) cm. These jets were discovered only recently (Dopita, Schwartz, & Evans 1982; Mundt & Fried 1983) but are probably the source of the momentum contained in the broader molecular outflows (Stahler 1992).

Such outflows are direct evidence that protostars can have a dramatic influence on their environment. The outflows observed near protostars are sufficiently energetic that their combined effects would suffice to drive gas out of star forming regions altogether, even in the absence of extremely massive and luminous stars. Here we will argue that these flows should also contain a dynamically insignificant poloidal field which, when summed over an entire galaxy undergoing its first burst of star formation, will lead to a large galactic seed field. This process is analogous to the way that the solar wind transports the poloidal field of the Sun outward, but the magnetic fields and radii of protostars are much larger, so the affect will be much greater. We will start by considering the minimal plausible value for the magnetic field of a protostar driving these
intense outflows. Once we have obtained this estimate we can consider whether such fields are likely to be entrained in the mass outflow and what the total effect of many such star forming regions is apt to be.
2. ESTIMATING THE MINIMUM GALACTIC SEED FIELD

Let’s start by considering a protostar embedded in a disk. The bulk of the disk is apt to be too dense and cool to contain a significant ionized component (Hayashi 1981; Umebayashi 1983; Umebayashi & Nakano 1988) although there are some indications that grains in the inner solar system were exposed to magnetic fields on the order of a gauss or so (Levy & Sonett 1978). Nevertheless, it is clear that close to the protostar the ionization fraction will be high and the gas will be a good conductor. Since the thermoelectric effect will be much more effective on small scales than on large ones, we expect the protostar to have a significant seed field, even if it forms in the absence of a strong galactic field. Moreover, we know that stars have strong internal dynamos, although we do not have a detailed understanding of their physical basis. One final point is that viable theories of jet formation all rely on some sort of magnetic driving mechanism. Taken together, these facts imply that protostars generate internal magnetic fields which are eventually strong enough to drive the dramatic outflows we see today. Since we are interested in deriving the minimal poloidal magnetic flux that should be imprinted on the outflow we need to know the minimum stellar field that could be expected to strongly bias the internal field of the surrounding disk, and the minimum stellar field that could be expected to drive outflows of the observed strength.

We will begin with the first question. This is complicated by the fact that the disk itself may contain a dynamo mechanism which might dominate its internal poloidal field. How can we be sure that the stellar field dominates? One simple test follows from considering the stability of a magnetic field in an accretion disk. A vertical field threading a conducting disk will be unstable
(Velikhov 1959; Chandrasekhar 1961; Balbus and Hawley 1991; Hawley and Balbus 1991). The consequent turbulence will induce local angular momentum transport equivalent to a dimensionless viscosity of $\alpha \sim V_A/c_s$, where $V_A$ is the Alfvén speed associated with the imposed field and $c_s$ is the local sound speed (Vishniac & Diamond 1992; Liang, Diamond & Vishniac 1993). Clearly this field will dominate the internal structure of the disk, and resist distortion by some internal disk dynamo, provided that $V_A \sim c_s > \alpha_d$ where $\alpha_d$ is the internally generated value of $\alpha$. This implies that there is a critical field strength for the protostar given by

$$B_{z,c} \sim \alpha_d (4\pi P)^{1/2}, \quad (4)$$

where $P$ is the pressure in the disk, evaluated near the inner edge of the disk.

Now in an $\alpha$ model disk (Shakura & Sunyaev 1973) the mass flow through the disk is approximately

$$\dot{M} \sim 3\pi \alpha_d P H \Omega \quad (5)$$

Therefore we can rewrite Eq. (4), dropping factors of order unity, as

$$B_{z,c} \sim \left(\frac{\alpha \dot{M} \Omega}{H}\right)^{1/2} \quad (6)$$

$$\sim \left(\frac{\alpha r}{H}\right)^{1/2} \left(\frac{\dot{M} \Omega}{r}\right)^{1/2}$$

where all these quantities are evaluated at the inner edge of the disk. In general the leading factor of $\alpha r/H$ will be of order unity or less. Wood & Mineshige (1989) have shown on phenomenological grounds that in cataclysmic variable disks $\alpha$ scales as $(H/r)$ to some power close to one. Angular momentum transport in low mass protostellar disks is unlikely to be more efficient than in fully ionized systems. It may be less efficient.

What protostellar magnetic field will be sufficient to drive significant mass loss from the disk? Observed jets in these systems have relatively high mass
fluxes and involve material flowing outward at hundreds of km/sec. Evidently the outward mass flux is comparable to the inward mass flux within the disk. Somehow a large fraction of the mass contained in the inner edge of the disk is diverted into a wind. The stellar magnetic field required to drive such an outflow is uncertain, but a model-independent minimal condition can be derived. The torque per unit area exerted by a dipole field that penetrates the disk is

\[ B_\theta B_\tau r / 4\pi \]

Assuming that the dipole field acquires a distortion of order unity (which should be about right if the star is rotating rapidly and reconnection occurs in the disk atmosphere) then this becomes critical when

\[ \frac{B^2 r}{4\pi \Sigma} = \alpha H^2 \Omega^2 \]  

or

\[ B_{z,c} \sim \left( \frac{\dot{M} \Omega}{r} \right)^{1/2} \]

For field strengths this large the torque exerted on a typical fluid element in the disk will be more important than the angular momentum transport due to processes internal to the disk. Large amounts of material will spiral outward, eventually turning into an intense outflow (as observed!). We don’t actually know how protostellar magnetic fields grow or saturate, but some kind of dynamo process should set in at the bottom of the Hayashi track, i.e. when a star is no longer fully convective. For ‘typical’ protostar values, i.e. \( \dot{M} \sim 3 \times 10^{19} \) gm/sec, \( r \sim 10^{12} \) cm, \( r\Omega \sim 10^7 \) cm/s, this gives a critical field strength of about 20 gauss. There is nothing unreasonable about a magnetic field of this strength. In fact, observational studies of T Tauri stars (Bouvier & Bertout 1989) suggest that as much as 10% of the surface is covered with photospheric spots with a typical local flux of 1300 gauss. Real fields might exceed the critical limit we have derived here by more than an order of magnitude. Work by Saar & Linsky (1985) and Basri & Marcy (1988) confirms that such field strengths are not unusual for late-type
active stars. For comparison we note that the Sun has an average dipole field of a few gauss. In what follows we will take a conservative line and invoke only the minimal field estimate derived above.

Since \( \alpha \sim H/r \) or less, a magnetic field strong enough to drive a strong outflow will necessarily be strong enough to penetrate into the inner regions of the surrounding accretion disk. This implies that the outflow will contain the current induced in the disk by the protostellar magnetic field. Moreover, since the outflow is composed of a hot, and well conducting, gas we expect that this current will tend to maintain the flux threading the outflow as it moves away from the star. The net affect will be to transport a flux, typical of the protostar at the epoch of outflow, out to large distances. Eventually this flux will be spread out over distances comparable to, or greater than, typical stellar separations. The strength of the field at this point depends on the number of separate current rings carried by the outflow. If the protostar undergoes \( N_m \) field reversals while ejecting matter, then outflow will contain \( N_m \) current rings, which will add incoherently to produce the total flux. Assuming the protostar reverses on a time scale of years, and the outflow persists for a few million years, this suggests an additional factor of \( 10^3 \). Observationally not much is known about the frequency of magnetic field reversals in such young stars, but their rotation periods are known to be short (on the order of a day) and one might expect on theoretical grounds (Parker 1955, 1979; for a recent treatment see Stix 1989) that this would indicate a proportionately shorter magnetic reversal time scale.

The total large scale field for the whole galaxy that is generated from the incoherent addition of the fields generated by \( N \) newly formed stars will be

\[
B_{seed} \sim \left( \frac{N N_m \dot{M} (\Omega r^2)}{g r^4} \right)^{1/2}
\] (9)
where \( r_g \) is the radius of the galaxy. In other words, the total large scale flux will be given by the incoherent addition of the contributing flux elements. In more physical terms this is due to the aggregation of the ejected current rings as the mass outflows from various protostars encounter one another. The star formation rate when the galaxy was young is not known precisely, but was probably at least 30 stars per year. Taking a dynamo growth rate of a few times \( 10^{-16} \text{sec}^{-1} \) this implies \( N \sim 3 \times 10^9 \). Then for \( r_g \sim 3 \times 10^{22} \text{cm} \) we get

\[
B_{\text{seed}} \sim 10^{-12} \text{gauss}
\]

which is 7-8 orders of magnitude larger than earlier suggestions based on known physics. The flattening of the poloidal field due to its confinement in the disk will produce a further amplification of \( B_r \) of about 30 so our final result is a minimal large scale field strength of \( \sim 3 \times 10^{-11} \) gauss.

We have assumed that the flux estimate should be made for a field strong enough to disrupt the disk at its inner edge. However, the field itself does not depend on input from the accretion disk and so will persist even after the disk is eroded. Moreover there is some evidence that at late times there may be some expulsion of mass from the protoplanetary disk even at rather large radii. For example, in our own solar system the gas of the protostellar disk appears to have been expelled out to well beyond the orbit of Mars. This may imply that young stars can support stronger magnetic fields, and therefore eject substantially more flux than the estimates given here. On the other hand, it may simply indicate that at late times the internal processes supporting the transfer of angular momentum within accretion disks become weak and even relatively modest fields can lead to a deep erosion of the protoplanetary disk.

We note in passing that this hypothesis depends on the advected flux acting passively, i.e. that separate current rings do not exert significant forces on one
another. One way of asking whether or not this is reasonable is to evaluate the typical field strength on scales that would typically separate protostars. If the associated magnetic field pressure is large compared to typical ISM energy densities then we have exaggerated the ability of protostellar outflows to seed the galactic magnetic field. For the numbers taken above and assuming the protostars are distributed evenly within the galactic disk, we find a typical separation of \( \sim 5 \) pc and a typical field strength on that scale of \( B_z \sim 10^{-10} \) gauss. This estimate ignores the amplification of \( B_T \) that comes from the flattening of the disk. If that affects all scales equally then this estimate needs to be raised to \( \sim 10^{-8.5} \) gauss. Of course, protostars are not distributed evenly at present, and probably weren’t at earlier epochs, but the modest size of this estimate suggests that local field required in this picture is dynamically insignificant.
3. CONCLUSIONS

It is disappointing to note that our results here are extremely approximate. A more precise estimate would require a detailed and plausible model for the generation of the outflow, a complete knowledge of the evolution of the disk and protostar as a function of the total mass, the initial mass function in the galaxy and a detailed understanding of the protostellar dynamo and the stability of the protostellar magnetic field. Nevertheless, the crude estimate we have arrived at here is sufficient to draw the following conclusions. First, the ejection of current rings from protostellar systems produces a galactic seed field with $B_r \sim 10^{-10.5}$ gauss. This is much larger than any other physically realistic seeding mechanism. Second, the generation of the seed field does not depend on the detailed history of the galaxy. This seeding process works equally well if the galaxy begins as a loosely associated cloud of star forming regions. Third, we still require a fast dynamo with a growth rate slightly more than $10^{-16} \, s^{-1}$ to grow microgauss fields in a little more than a billion years. The large uncertainties in the seeding process can only change this estimate by some logarithmic factor.

We note that the existence of galactic dynamo is still somewhat controversial. Kulsrud (1990) has suggested that any such dynamo should overproduce small scale fields. Since his calculation assumed that such fields were essentially passive this objection may not be realistic. On the other hand, Vainshtein & Cattaneo (1992) have posed an objection, in principle, to any fast dynamo process. Since real astrophysical systems would be difficult to understand if fast, large scale, dynamos were actually impossible, it seems likely that nature has some way of evading this objection (for one such suggestion see Vainshtein, Parker, & Rosner...
Here we simply note that this work assumes such a dynamo is possible. If not, then our seeding mechanism is insufficient to explain galactic magnetic fields.

It is interesting to compare this process to one based on flux ejection from collapsed objects. There are at least two basic difficulties encountered in trying to apply a similar idea to black holes. First of all, the energy required for escape from a black hole is such that subsequent escape from the galaxy can be avoided only if the jet plows into a large column density of interstellar gas. This implies that large black holes may produce jets, as seen in AGN, but will have some difficulty in mixing ejected flux into the galactic disk and halo. Second, the small radius of a black hole tends to imply a small magnetic flux. On the other hand, black holes may have a much shorter field correlation time scale and may eject a much larger number of independent current rings.

Suppose we consider the ejection of flux from a central black hole in our galaxy (Hoyle 1969; Daly & Loeb 1990). A $10^6 M_\odot$ black hole, accreting at the Eddington limit will have a mass accretion rate $\sim 10^{24}$ gm/s and a radius of $3 \times 10^6$ km. Consequently its characteristic flux will be $\sim 10^{29}$ gauss cm$^2$ or about 5000 times the flux associated with any single protostar. If the black hole magnetosphere changes its magnetic structure in just a few light crossing times than over the course of a few tens of millions of years it may eject as many as $10^{13}$ current rings, as compared to the $\sim 10^{6.5}$ ejected by a protostar. We can conclude from this that the flux ejection from a central black hole in our galaxy might be more effective by a factor of order unity. On the other hand, in addition to the difficulty of mixing the ejected flux from a black hole into the ISM it may also be that true the magnetic field of the black hole magnetosphere is maintained by flux accreted from the surrounding disk. In this case the magnetic flux estimate may be too large by a factor of $\alpha r/H$, which is probably of order unity, and a factor which is a ratio of the correlation time scales for the poloidal field in
the accretion disk to light travel time across the black hole magnetosphere. The latter factor is difficult to estimate, but is presumably a number substantially less than one. Finally, it seems doubtful that the formation of such a large black hole preceded the epoch of star formation.

We might instead consider a population of solar mass black holes. In this case the jets, although still narrowly focussed, are much more likely to have mixed with the ISM. The total number of such objects is hard to estimate now, let alone at earlier epochs, but if we express the total mass in such objects in units of $10^6 M_\odot$ then since the radius of a black hole, and its Eddington accretion rate, are proportional to its mass we find that the total seed flux contributed by such a population would be reduced from our previous estimate by a factor of $10^{-3} M_6^{1/2}$, where $M_6$ is the total mass of the population in units of $10^6 M_\odot$. It would appear that such a population is unable to produce a dominant contribution to the galactic seed field.

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