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A POSSIBLE ORIGIN OF GALACTIC MAGNETIC FIELDS

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ABSTRACT

Large-scale galactic magnetic fields with strengths of several μG can result if galaxies typically undergo a brief but active phase during which magnetized plasma is channeled away from a central compact object through jets. When the jets are initially activated, they must tunnel through the ambient protogalactic medium, and, as they do so, material from the jets flows into the protogalactic medium. It is shown that if these jets possess magnetic fields with equipartition field strengths and large coherence lengths, then galactic fields with large coherence lengths and equipartition field strengths result, which suggests another possible origin of galactic magnetic fields. Observations of jets are consistent with the fields having large coherence lengths and equipartition field strengths, making the proposed model viable. The jet magnetic fields may be generated near the central compact object, and, subsequently, may be stretched and amplified by processes within the jets; this interpretation of the ultimate source of the field is not mandatory in this model, but it is discussed for completeness. Implications of the model are considered.

Subject headings: galaxies: jets — hydromagnetics — interstellar: magnetic fields

I. INTRODUCTION

The origin of galactic magnetic fields remains enigmatic. Several models have been proposed (see e.g., Sofue, Fujimoto, and Wielebinsky 1986; Rees 1987 and the references therein), such as dynamo amplifications of a seed magnetic field (e.g., Parker 1979; Stix 1975, 1976; Zeldovich, Ruzamin, and Sokoloff 1983). Dynamo theories, however, have difficulty explaining the existence of strong magnetic fields in some high redshift objects, since at least a few rotation periods are required for the seed fields to be sufficiently amplified. For example, the damped Lyα systems at a redshift of about two have undergone less than one rotation, yet possess magnetic fields of order 10 μG (Wolfe 1987), which cannot be produced via the standard dynamo model. In addition to observational difficulties, theoretical problems seem to be looming on the horizon for the dynamo model: Kulsrud (1989) argues on theoretical grounds that large field strengths *and* large coherence lengths cannot be produced via dynamo amplification; although Ruzmaikin, Shukurov, and Sokoloff (1988) might argue otherwise.

Alternatively, a primordial origin of galactic magnetic fields has been suggested (Piddington 1964, 1972, 1978; Ohki *et al.* 1964). However, the production of such a field encounters major theoretical difficulties (see e.g., Quashnock, Loeb, and Spergel 1989, and the references therein). Hence, there is no consensus as to the origin of galactic magnetic fields. And, the two models discussed above face observational and theoretical difficulties.

An alternative model is presented here. Jets emanating from a central compact source channel magnetized plasma away from the central compact source and, during the early evolutionary stages of the galaxy, plasma will flow from the jets into the protogalactic medium (Daly 1990). This could be the source of galactic magnetic fields if most galaxies undergo such an active phase, which may be quite short-lived.

The properties of galactic magnetic fields have been studied in detail for some nearby galaxies. Several spiral galaxies in our vicinity have measured magnetic field strengths which typically fall in the range from 3 to 12 μG (Sofue, Fujimoto, and Wielebinsky 1986). The fields generally have either a ring or bisymmetric spiral field configuration. In the ringlike configuration the field lines are closed and roughly concentric being centered near the center of the galaxy. Hence, galaxies with this field configuration have zero net flux. Galaxies with the bisymmetric spiral field configuration possess field lines which appear to begin at large galactocentric radii, curve into the central regions of the galaxy, reverse direction, and exit again at large galactocentric radii, and sometimes appear to "thread" the nuclear region maintaining the direction of the field. It is not known where these field lines close: they may close at very large galactocentric radii, or out of the plane of the disk at scale heights large relative to the disk scale height, where the density of charged particles is too low for the field to be measured. Alternatively, the field lines could connect to intergalactic field lines, if an intergalactic field exists.

A small fraction of extragalactic sources are radio sources which possess jets (e.g., Bridle and Perley 1984). However, most galaxies could have been a radio source for a brief period of time without violating the counts of extragalactic radio sources. The properties of the jets during this hypothetical phase of activity may be inferred from the observed properties of radio jets.

Magnetic fields are consistently found in radio jets through polarization studies (e.g., Miley 1980; Saikia and Salter 1988). Typically, these magnetic fields have equipartition field strengths of ~ 10 μG, and coherence lengths of about several kpc; field strengths of 30 μG and longitudinal coherence lengths of 20 kpc have been observed (e.g., Perley, Bridle, and Willis 1984).

The field configuration within the jets is not known; the field may be in large closed loops (e.g., Begelman, Blandford, and Rees 1984), or there may be a net flux within the jet if the field lines threading the jet close outside the jet.

The magnetic field strength in jets can be measured directly if both X-ray and radio data are available for a given object, since the same relativistic electrons producing the synchrotron emission inverse Compton scatter low-energy photons to X-ray energies, and the ratio of the intensity of the radio emission to the X-ray emission depends on the magnetic field strength. For the two cases in which these data are available the measured field strength is in the vicinity of the equipartition value (Miley 1980).

The fields within jets are thought to originate near a central compact object. The flow of plasma from the central object through the jets carries and stretches the magnetic field lines, increasing their longitudinal scales appreciably. There must be processes occurring near the central compact object and within the jet to produce magnetic fields with large coherence lengths (see the discussion by DeYoung 1980).

Here, we consider the possibility that galaxies which have a magnetic field possess a central compact source (not currently active), and undergo an active phase (which may be short-lived) during which jets channel energy away from the central compact object. These jets must carve a channel through the galactic medium and when they do so jet material flows into the region adjacent to the jet (Daly 1990). This model is described in § II, where it is shown that the total magnetic energy that flows into the galactic medium over the period during which the jets are tunneling through this medium yields a magnetic field strength which is comparable to the observed galactic value. In § III the generation of magnetic fields near the central compact objects is considered. The results are discussed in § IV.

This idea has its predecessors. In 1969, Hoyle suggested that the magnetic fields generated near a central compact object could be responsible for the build up of galactic magnetic fields. And, in 1987, Rees suggested that the origin of the galactic magnetic fields is related to the field observed in radio sources.

II. THE MODEL

The general picture is that each galaxy that has a magnetic field possesses a central compact object, and this object was active for at least a short period of time during the early evolutionary stages of the source (protogalaxy or galaxy, referred to as a protogalaxy). The jets must carve a channel through the protogalactic medium and, as they do so, material flows into that medium (Daly 1990), hence, the magnetic field frozen into the jet plasma is carried into the galactic medium. Here it is shown that if the material flowing through the jets carries a magnetic field with equipartition field strength and a coherence length of approximately a few kpc, then the field deposited in the protogalactic medium during this phase can be identified with the currently observed galactic magnetic field.

As the jets tunnel through the protogalactic medium they shock heat a large volume of gas; the shock heated volume extends a considerable distance in the direction perpendicular to the jet axis. Due to the pressure gradient between the inner shock and this region (discussed below), the jet plasma flows into the cocoon after it has been shock heated (see Fig. 1). We assume that the expansion of the magnetic field carried by the plasma from the jet into this volume is adiabatic. Later, as the system evolves, it acquires angular momentum and the gas falls into a plane which is identified with the galactic disk. The magnetic field accompanies the gas and is also swept into the plane of the galactic disk; it is assumed that the magnetic field strength is adiabatically varied during this compression. Hence, the final galactic field strength may be estimated in terms of the initial (jet) field strength and the relative volume occupied by the jets and the galactic disk. The final coherence length of the field will be on the order of the coherence length of the field jets, although the field may have been stretched, contorted, or amplified by the complex processes which must occur during the early evolutionary stages of the galaxy.

Consider a compact object embedded in the center of a gas cloud (such as a galaxy or protogalaxy) and ejecting material at supersonic velocities along two, well collimated, oppositely directed jets. The plasma flowing through the jets is assumed to carry a magnetic field with equipartition field strength and with a large coherence length. In the early stages of the evolution of the system the jets must tunnel through the ambient gas associated with the galaxy (or protogalaxy). This process sets up two coupled shock systems (Daly 1990; see also Pacholczyk 1983), as illustrated in Figure 1. The outer shock contains the shocked ambient gas and the inner shock contains the shocked jet plasma and hence the magnetic field. The pressure gradient between the inner shock and the adjacent shocked ambient gas causes the magnetized plasma to flow from the inner shock to the surrounding galactic medium, into the region defined by the shock envelope (labeled the "cocoon" in Fig. 1). Although

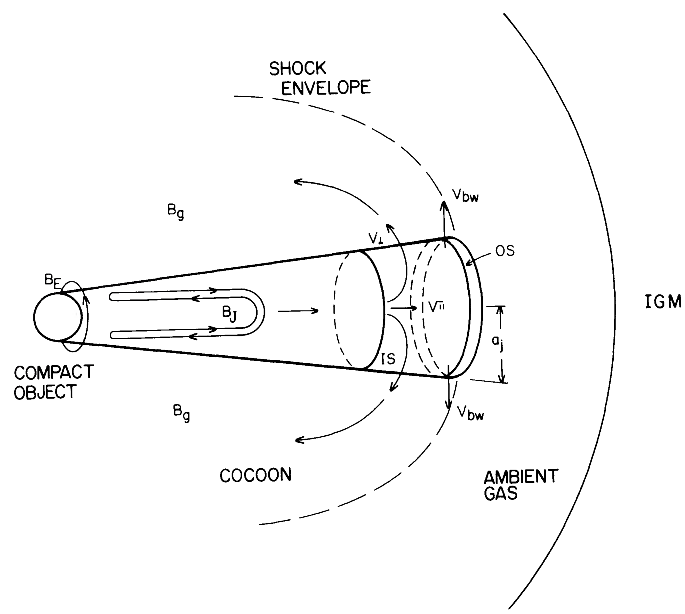

FIG. 1.—The supersonic jet tunneling through the galactic medium (ambient gas) and the flow of the jet plasma ($v_\perp$) carrying the magnetic field from the inner shock (IS) into the shocked ambient gas (the cocoon). Two coupled shock systems are displayed. A driven shock wave forms along the symmetry axis of the jet: the outer shock (OS) contains the shocked ambient gas and the inner shock (IS) contains the shocked jet plasma; a contact discontinuity separates these two regions. The pressure discontinuity between the gas in the outer shock and the adjacent ambient gas causes a blast wave to propagate perpendicular to the driven shock wave, with a velocity v_{bw}. The shock envelope is the boundary between the shocked and unshocked ambient gas, and the cocoon is the region interior to the shock envelope. A small pressure gradient exists between the plasma in the inner shock near the contact discontinuity and the adjacent shocked ambient gas in the cocoon. This causes the magnetized plasma to flow from the inner shock into the cocoon with a velocity $v_\perp$. In the rest frame of the compact object the plasma in the inner shock has a velocity $v_{||}$ parallel to the jet axis. The cross sectional radius of the jet, a_J, may vary with distance along the jet axis. A second jet, which is a symmetric counterpart to the jet shown here, is assumed to emanate from the opposite side of the compact object. For more details, see Daly (1990).

the flow may be highly turbulent in the vicinity of the shocks, the small scale eddies that may form will be averaged out by the large scale magnetic fields streaming with the plasma flow.

The magnetic field lines are frozen into the plasma, and hence are carried into the galactic medium by the plasma flowing from the inner shock to the adjacent ambient gas (see Fig. 1); this results from the extremely high conductivity of the shocked plasma. The magnetized plasma flows with a longitudinal velocity $v_{\parallel}$, and a transverse velocity $v_{\perp}$ perpendicular to the symmetry axis of the jet. Subsequently, the magnetic flux is assumed to be conserved, and the average field strength B decreases adiabatically with respect to the volume V it occupies, $B \propto V^{-2/3}$.

The jet plasma carries a field of strength B_J from an effective volume $V_{\rm eff} = v_{\perp} A_{\perp} t$ into the cocoon volume V_c, where $A_{\perp}$ is the area through which the magnetized fluid flows for a period t; $A_{\perp} = 2\pi a_J l$, where $2a_J$ is the cross-sectional diameter of the jet, and l is the length of the cylindrical boundary across which the flow occurs: $a_J/l \approx v_{\perp}/v_{\parallel}$. Since there are two jets, $V_{\rm eff} \simeq 4\pi a_J^2 v_{\parallel} t$. The longitudinal fluid velocity in the inner shock near the contact discontinuity is given by $v_{\parallel} \approx 0.75 \times v_s$ where v_s is the velocity of the forward shock front. The velocity v_s remains approximately constant due to the continuous energy input to the shock system from the jet (Daly 1990). The time t over which the outflow into the galactic medium occurs is approximately the period over which the jets are tunneling to the edge of the galaxy, $t \simeq t_g \simeq R_{ge}/v_s$, where R_{eg} is the radius of the galaxy at this early evolutionary epoch. Hence, $V_{\rm eff} \approx (\pi a_J^2 R_{ge})$, and the cocoon volume V_c is filled with a magnetic field of magnitude B_c, given by

$$B_c \simeq \left(\frac{\pi a_J^2 R_{ge}}{V_c}\right)^{2/3} B_J \, . \tag{1}$$

The present value of the galactic magnetic field, B_g, be estimated assuming that the magnetic energy density varies adiabatically. Equation (1) then yields,

$$B_g \simeq \left(\frac{a_J}{h}\frac{a_J}{R_g}\frac{R_{ge}}{R_g}\right)^{2/3} B_J \, , \tag{2}$$

where the present galactic field is assumed to occupy a disk of an approximate volume: $2\pi R_g^2 h$, where h is the scale height of the disk, and R_g is its radius. Typically, $a_J \simeq h \simeq 0.5$ kpc, $R_g \simeq R_{ge} \simeq 10$ kpc, so $(a_J/R_g) \sim 0.05$ (note that R_{ge} may be significantly larger than R_g). This yields an expected present day galactic field strength of $B_g \simeq 0.2 B_J (R_{ge}/R_g)^{0.66}$. The typical jet fields of $\sim 10\ \mu$G give rise to a galactic field of strength $\sim \mu$G, which is comparable to observed values. In addition, the field is expected to have a large coherence length characteristic of the fields in jets, on the order of several kpc. The field lines within the jets are expected to be closed, either in a ringlike configuration (as shown in Fig. 14 in Begelman, Blandford, and Rees 1984) or a horsehoe like configuration (see Fig. 1; see also Fig. 13 in Begelman, Blandford, and Rees 1984), although it is also possible for there to be a net flux in the jet if the magnetic field lines thread the jet and close outside the jet. Hence, the field lines in the galactic medium are expected to be closed: the system as a whole is expected to have zero net flux. It is not known whether galactic magnetic fields possess a net flux: the field lines in galaxies with a ringlike configuration are apparently closed; those in galaxies with a bisymmetric configuration may close above the plane of the galaxy or at large galiocentric radii, where the particle number density is too low for the field strength and direction to be measurable, hence the field lines in galaxies with a bisymmetric field configuration may also be closed.

If the field is initially smaller than the equipartition field strength, it may be increased via dynamo amplification. It is not expected to be amplified to values greater than the equipartition value since backreaction prevents further amplification.

An intergalactic magnetic field could result from extinct radio sources, as discussed by Rees (1987). In the model considered here, after the jets tunnel through the galactic medium, they propagate into the intergalactic media (hereafter IGM) dumping magnetic energy into the IGM. The total magnetic-field energy which is carried into the IGM depends on how long the central source is active and continues to eject magnetized plasma through the jets. If the central compact source is active for a time scale $t_{\rm on}$ which is $\lesssim 10^7$ yr, the rotation of the galactic system may be neglected since the time scale for galactic rotation is $t_{\rm rot} \simeq 2.5 \times 10^8 (R/10\ {\rm kpc})(v_{\rm rot}/250\ {\rm km\ s^{-1}})^{-1}$ yr, where R is the radial distance from the center of the galaxy, and $v_{\rm rot}$ is the circular rotational velocity. The magnetized plasma which has been channeled into the IGM will adiabatically expand until coming into pressure equilibrium with the IGM, and may eventually fill the intergalactic volume. The expected mean value of the intergalactic magnetic field depends on how long typical sources continue to channel magnetized plasma through the jets, and on how many galaxies have undergone a phase of this type, and hence is rather uncertain. A rough estimate of the average field strength in the IGM at the present epoch may be obtained assuming that the jet field adiabatically expands to fill the volume between galaxies, $V_{\rm IGM}$:

$$B_{\rm IGM} \sim \left(\frac{V_J}{V_{\rm IGM}}\right)^{2/3} B_J \sim (\pi a_J^2 l_J n_g)^{2/3} B_J \, , \tag{3}$$

where l_J is the final length of the jet, $l_J \simeq v_s t_{\rm on}$, and n_g is the comoving number density of galaxies which have undergone a jet phase. For typical values of $l_J \sim 100$ kpc (i.e., $v_s \sim 10^4$ km s^{-1} and $t_{\rm on} \sim 10^7$ yr), $B_J \sim 5\ \mu$G, $a_J \sim$ kpc, and an average number density of galaxies undergoing a "tunneling" phase of this type, $n_g \sim 0.01\ {\rm Mpc^{-3}}$, equation (3) implies $B_{\rm IGM} \sim 10^{-11}$ G, which is below the observational upper bound of 3×10^{-11} G (Vallee 1983). Hence, the model is not seriously constrained by the upper limits on the IGM field.

If the galaxy is in a cluster of galaxies this process will lead to a magnetic field in the intracluster medium, with a field strength significantly larger than that estimated for the intergalactic magnetic field.

III. MAGNETIC FIELDS IN JETS

Various models may account for the existence of magnetic fields in the vicinity of massive black holes, especially if they are rotating. Among these are: dynamo amplification processes in accretion flows (Bisnovatyi-Kogan and Vainstein 1971; Bisnovatyi-Kogan and Ruzamaikin 1975; Pudritz 1981; Zeldovich, Ruzamaikin and Sokoloff 1983), general relativistic effects in the Kerr metric (Blandford and Znajek 1977; Phinney 1983; Rees 1984), and the Biermann effect (Biermann 1950; Mestel and Roxburgh 1962; Roxburgh 1966; Mestel and Moss 1983; Loeb 1988). The last effect does not require any seed field in the accreting medium near the compact object. In any case, the dominant mechanism is expected to saturate at a magnetic field amplitude close to equipartition with the matter energy density near the compact object.

The Eddington luminosity of an object of mass M is $L_E = 4\pi GMm_p c/\sigma_T = 1.3 \times 10^{44} M_6$ ergs s^{-1}, where M_6 is the mass of the object in units of $10^6\ M_\odot$. For black holes, this luminosity may also be expressed as $L_E = n_E m_p c^3(4\pi r^2_{\rm Sch})$ where the proton density is $n_E \equiv (c^2/4\sigma_T GM) = 2.4 \times 10^{12} M_6^{-1}$ cm^{-3}, the Schwarzschild radius is $r_{\rm Sch} = (2GM/c^2) = 3 \times 10^{11} M_6$ cm, m_p is the proton rest mass, and c is the velocity of light. The corresponding equipartition magnetic field is, $B_E = (8\pi n_E m_p c^2)^{1/2} = 3 \times 10^5 M_6^{-1/2}$ G (Rees 1984). If the luminosity of the object is some fraction η of the Eddington luminosity, the magnetic field strength is scaled down by $(\eta)^{1/2}$. In addition, the actual magnetic pressure may be a fraction ϵ of the Eddington energy density. Dynamo amplification of the magnetic field up to the Eddington energy density in accretion flows near a rotating compact object occurs on the dynamical time scale of the accretion flow (Bisnovatyi-Kogan and Vainstein 1971), which is quite rapid. These fields may then be carried by the plasma flowing through the jets. As the field is carried through the jet, the transverse magnetic field strength is expected to vary in inverse proportion to the jet radius a_J, while the longitudinal component is expected to vary as a_J^{-2} (e.g., Bridle 1982). If it is supposed that the longitudinal and transverse components of the field as it begins to flow into the jet are on the same order, and that the jet has a constant, nonzero opening angle, then the transverse component rapidly becomes larger than the longitudinal field and the field strength is given by

$$B_J \sim \left(\frac{r_{\rm Sch}}{a_J}\right)\sqrt{\epsilon\eta}B_E \sim 10\sqrt{\frac{\epsilon\eta}{0.1}}\left(\frac{\rm kpc}{a_J}\right)M_6^{1/2}\ \mu{\rm G}\ . \quad (4)$$

For $M_6^{0.5}(\epsilon\eta/0.1)^{0.5} \sim 1$ this expression is in fair agreement with the equipartition field strengths in jets; however, polarization studies indicate that the field direction is often longitudinal. This equation would be applicable to the longitudinal field component if the field strength is set by the transverse component of the field, and there were processes occurring within the jet which significantly stretch the longitudinal component of the magnetic field, such as shear effects (e.g., Begelman, Blandford, and Rees 1984).

Many observed jets are found to have large scale longitudinal magnetic fields, which may be several tenths of the total jet length, for example, NGC 6251 (Perley, Bridle, and Willis 1984) has a coherence length of about 20 kpc, and the jet length is $\sim$115 kpc.

The longitudinal field must result from processes occurring within the jets, if the jets have a constant, nonzero opening angle. As the field lines are carried away from the compact object they may be significantly stretched, and hence become predominantly longitudinal with large coherence scales; this may result from shear effects caused by the velocity gradient across the jet (Begelman, Blandford, and Rees 1984); such velocity gradients may be a common feature in jets (Daly and Marscher 1988). Unless the longitudinal field lines reverse direction, Magnetic flux amplification is needed to account for the inferred (from observations) equipartition fluxes of 10^{39}–10^{41} G $\times$ cm^2 across the jets, since the maximum longitudinal magnetic flux that can be extracted by the jet near the horizon of the central black hole is limited to values of about $4\pi B_E r^2_{\rm Sch} \sim 10^{34}$ G $\times$ cm^2, even for $M = 10^9\ M_\odot$ (Begelman, Blandford, and Rees 1984). Thus, either the direction of the field lines within the jet reverses numerous times or the magnetic flux is significantly increased by processes occurring within the jet (see the discussion by Scheuer 1987).

Finally, it is interesting to note that equations (2) and (4) yield the following expression for the galactic magnetic field,

$$B_g \sim 3\sqrt{\frac{\epsilon\eta}{0.1}}\left(\frac{a_J}{\rm kpc}\right)^{1/3}\left[\left(\frac{10\ {\rm kpc}}{R_g}\right)\left(\frac{0.5\ {\rm kpc}}{h}\right)\left(\frac{R_{ge}}{R_g}\right)\right]^{2/3} M_6^{1/2}\ \mu{\rm G}\ . \quad (5)$$

Note however, that equation (4) is only applicable if there is some process occurring within the jet which will substantially increase the longitudinal field strength (see the discussion following equation [4]).

For our galaxy equation (5) predicts the existence a central black hole with a mass of $\sim 10^6\ M_\odot\ (R_g/R_{ge})^{4/3}(\epsilon\eta/0.1)^{-1}$, in order to account for the observed magnetic field strength $B_g \sim 3\ \mu$G; this result is consistent with the observational upper bound of a few $\times\ 10^6\ M_\odot$ on the mass of a compact object in our galactic center (Genzel and Townes 1987). The requisite mass of the compact object may be much smaller than $10^6\ M_\odot$ if R_{ge} is larger than R_g, or if dynamo amplification played a significant role in increasing the initial magnetic field carried into the galactic medium from the jets.

In order for a sufficient field strength to be present in the galaxy today the jets must be active for at least $t_{\rm on} \sim 10^6$–10^7 years. The maximum jet lifetime is $t_{\rm max} \sim \beta Mc^2/(\eta L_E) \sim 4 \times 10^8 \beta/\eta$ yr, where β ($\sim$0.1), is the emission/accretion power efficiency; hence, there is more than sufficient time for the magnetic field to be deposited in the protogalactic medium.

IV. DISCUSSION

A far reaching implication of the model described here is that any system which possesses a magnetic field must either contain a central compact object that was once active and produced large-scale jets, or the system formed in a region sufficiently close to such an object. The second possibility arises because magnetized plasma from the jets flows into the surrounding intergalactic medium after the tunneling process through the galactic medium has been completed, and before the rotation of the system becomes important. Hence, a system which forms from gas which was mixed with magnetized jet plasma will possess a magnetic field upon collapse, which could then be further amplified via the dynamo mechanism.

The existence of strong magnetic fields in high redshift objects, such as the damped Lyα systems, poses a major problem for the dynamo amplification models because there has not been sufficient time for the seed field to be amplified to the observed field strengths (Wolfe 1987). It can be understood in the context of the model presented here. Suppose that, at an early epoch, the system was active and deposited a jet magnetic field into the ambient medium of the system, and that subsequent to the active phase hydrogen gravitationally accumulated onto the system. Then a damped Lyα system with a large magnetic field would result: the newly accumulated hydrogen and magnetic field need not be mixed to explain the field seen by Wolfe (1987) since it is only known that the two are spatially correlated. Note that the galaxy will not be detectable as a damped Lyα system during the phase when it is active, since during this phase the column density of neutral hydrogen will be small. Conversely, the damped Lyα systems need not be radio sources.

An interesting consequence of this model is that some galaxies which do not undergo this type of process (the tunneling of jets through the medium) might not possess magnetic fields, although they may have acquired initial magnetic fields if they collapsed from gas which had a magnetic field injected into it from nearby galaxies which did undergo a tunneling phase.

A necessary ingredient of this model is that the magnetic fields within the jets have equipartition field strengths, and large coherence lengths. When X-ray data becomes available from *ROSAT* and *AXAF* for sources with radio jets, it will be possible to combine the radio and X-ray data to determine the magnetic field strength. If the field strengths are significantly less than the equipartition value than this model for the origin of galactic magnetic fields may be ruled out; unfortunately, field strengths which are comparable to equipartition will not confirm this model.

Galaxies which undergo a phase of this type that are in a cluster or protocluster of galaxies will significantly enrich the cluster medium with magnetized plasma when the tunneling through the galactic medium is completed and the jets begin interacting with the intracluster gas. This could provide an origin of the magnetic fields in the intracluster medium. Enrichment of the cluster medium from radio sources is discussed in more detail by Rees (1987).

The presence of a magnetic field may significantly alter the initial mass function in star-forming regions (Rees 1987). Hence, the initial mass function for stars which form in the galaxy prior to the flow of the magnetic field from the jets into the medium may be substantially different from that subsequent to this event. So, the initial mass function for stars forming early in the life of the galaxy may be very different from that inferred from stars observed in our galaxy today.

The magnetic field in this model originates from the central compact object and/or from processes occurring within the jet. Presumably the ultimate source of the field is dynamo amplification; in this sense this model is a variant on the standard dynamo amplification model. Instead of generating the field in the galactic medium, the field is generated near a central compact object and is stretched and amplified in the jet, or it may be generated in the jet; the field subsequently is carried into the galactic medium by the plasma flow from the jet.

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