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Magnetic monopoles and the survival of galactic magnetic fields

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The most stringent, mass-independent limit on the flux of magnetic monopoles is based upon the survival of the galactic magnetic fields, the so-called "Parker limit": $F \lesssim 10^{-16}$ $cm^{-2}sr^{-1}sec^{-1}$. We reexamine this limit, taking into account the monopole's mass and velocity distribution, and the observed structure of the galactic magnetic field. We derive flux limits which depend upon the monopole's mass and velocity, and the strength, coherence length, and regeneration time of the galactic magnetic field. The largest monopole flux consistent with both the survival of the galactic magnetic field and the bounds from the mass density contributed by monopoles is $F \simeq 10^{-12}$ $cm^{-2}sr^{-1}sec^{-1}$, arising for monopoles of mass $\simeq 10^{19}$ GeV with velocity $\simeq 3\times 10^{-3}c$ which cluster with the Galaxy. An observed flux greater than this would have profound implications for our understanding of the galactic magnetic field, and we briefly explore some exotic possibilities. Of course, this bound is not applicable to a local source (e.g., the Sun, atmospheric cosmic-ray production, etc.).

I. INTRODUCTION

Dirac[1] pointed out that it is *possible* to add magnetic monopoles to electromagnetism in a consistent manner only if their magnetic charge is $h = n\,2\pi/e \cong n(137e/2)$ $(n = 1,2,3,\ldots)$. In 1974 't Hooft and Polyakov showed that magnetic monopoles are *obligatory* in the low-energy theory if $U(1)_{EM}$ is embedded in a larger, simple group G.[2] Specifically, they showed that topologically stable configurations of the gauge and Higgs fields with magnetic charge $h = n(2\pi/e)$ and mass (i.e., energy associated with the field configuration) $m \simeq hv$ necessarily exist when G breaks down to $G' \times U(1)$. The quantity v is the energy scale associated with the spontaneous breakdown of the simple group G to a subgroup $G' \times U(1)$ which contains an explicit U(1) factor.

Of course, just such an embedding is the goal of grand unification. In the simplest unification scheme, the Georgi-Glashow SU(5) model,[3] in which $SU(5) \rightarrow SU(3) \times SU(2) \times SU(1)$ at a scale $v \simeq 10^{14}$ GeV, $m \simeq 10^{16}$ GeV. In the very early Universe ($t < 10^{-36}$ sec, $T > 10^{15}$ GeV) the full SU(5) symmetry should be restored by finite-temperature effects.[4] When symmetry breaking occurs ($T \sim 10^{14}$ GeV), it has been argued that ~ 1 monopole should be produced per horizon volume, since monopoles can be viewed as "topological defects" in the Higgs field, and causality prevents the Higgs field from being "smoothed out" on scales greater than the horizon. Their subsequent annihilation is negligible, and the mass density associated with this predicted relic abundance is a factor of 10^{12} greater than the limit on the present mass density of the universe.[5] A variety of viable, but uncompelling scenarios have been suggested to suppress their initial abundance.[6,7] However, this is not the concern of this paper.

Clearly, the discovery of a magnetic monopole would be of tremendous significance. If such a particle were discovered and if its mass were $\sim 10^{16}$ GeV, it would be a striking confirmation of the ideas of grand unification, and just as importantly, evidence that the Universe was once hotter than $\sim 10^{14}$ GeV. In addition, as we shall argue, if the detected flux were greater than the flux limit based upon the survival of the galactic magnetic field, its discovery would force us to alter drastically our ideas about the galactic magnetic field and its dynamics. The flux $\simeq 10^{-9}$ cm^{-2} sr^{-1} sec^{-1} inferred from the recent candidate monopole event reported by Cabrera[8] does in fact exceed the limits we shall derive by about three orders of magnitude.

The flux bound based upon the survival of the galactic field is rather straightforward.[9–11] If the galactic field is due to persistent currents, as the case seems to be since $\nabla \times \vec{B}_{gal} \neq 0$, then monopoles which move along field lines gain kinetic energy at the expense of the field, and the currents are reduced. The survival of the galactic field requires

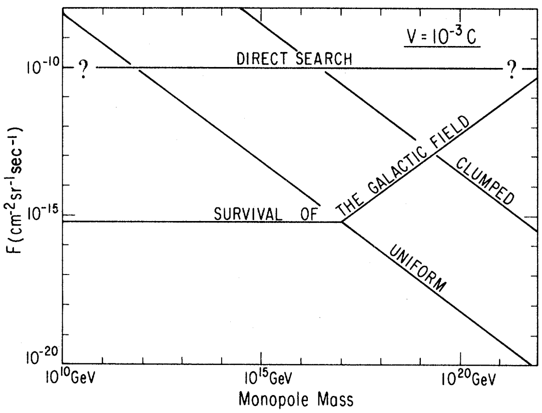

FIG. 1. Summary of monopole flux limits as a function of monopole mass for an initial monopole velocity of $10^{-3}c$, valid for uniform or isotropic velocity distribution. The lines marked "uniform" and "clumped" are based upon the mass density of the Universe and Galaxy, respectively. The "direct search" limit is based upon Refs. 30, 32, and 33 and is applicable for $2\times 10^{-2}c \gtrsim v \gtrsim 3\times 10^{-4}c$. However, because of uncertainties with regard to the ionization losses of a slowly moving monopole (Ref. 31), the validity of this bound is in question. The limit based upon the survival of the galactic magnetic field is the flux bound derived in this paper. A monopole mass of $\sim 10^{17}$ GeV separates the two regimes: (i) $v \lesssim v_{\rm mag}$, where monopoles are easily deflected by the magnetic forces, and (ii) $v \gtrsim v_{\rm mag}$, where the magnetic force is a small perturbation to the monopole's motion.

that the field energy not be dissipated more rapidly than the currents can be regenerated by dynamo action, say $t_{\rm reg} \simeq 10^8$ yr (Ref. 9). This implies that for a directed flux $F \lesssim 10^{-16}$ cm^{-2} sr^{-1} sec^{-1} (Refs. 10 and 11).

In this paper we carefully reexamine the original simple arguments, taking into account the monopole's mass and velocity distribution and the observed structure of the galactic field (strength, coherence length, regeneration time, etc.). For monopoles more massive than $\sim 10^{16}$ GeV, the flux bound is *less* restrictive than the bound just mentioned, and depends upon the monopole's mass and velocity. However, when these limits are combined with the flux bounds based upon the contribution of the monopoles to the mass density of the Galaxy and of the Universe, we find that, with the most favorable asssumptions (for monopoles), the maximum permissible flux is $F \simeq 10^{-12}$ cm^{-2} sr^{-1} sec^{-1} (all these flux limits are summarized in Figs. 1–3). This flux is allowed for a distribution of monopoles with mass $\sim 10^{19}$ GeV and velocity $\sim 3\times 10^{-3}c$ which cluster with the Galaxy. A flux

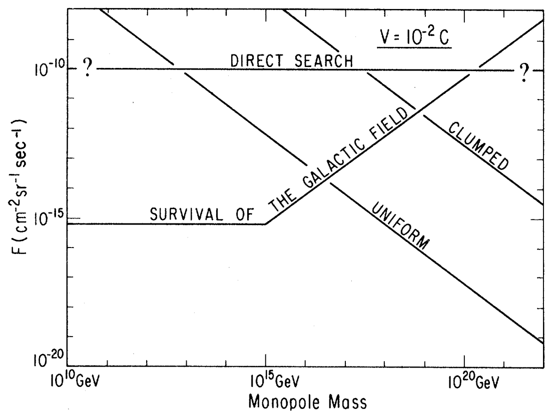

FIG. 2. Same as Fig. 1, except for a monopole velocity of $10^{-2}c$. It is unlikely that monopoles with velocity $v \simeq 10^{-2}c$ could remain clustered with the Galaxy since $v_{\rm escape} \simeq 2\times 10^{-3}c$; however, the bound has been included for completeness. The change in the slope of the galactic magnetic field bound for $v \simeq v_{\rm mag}$ occurs for a monopole mass of $\sim 10^{15}$ GeV.

greater than this is essentially impossible to reconcile with our present understanding of the galactic magnetic field. Of course these arguments do not preclude "local sources," e.g., cosmic-ray interactions, the Sun, etc.

The paper is organized as follows. First, in Sec. II we review the structure of, and the observational evidence for, the galactic magnetic field. Next, in Sec. III we derive our refined limits on the flux of magnetic monopoles based upon the survival of the magnetic field of the Galaxy. Then in Sec. IV we summarize the flux limits based upon mass densi-

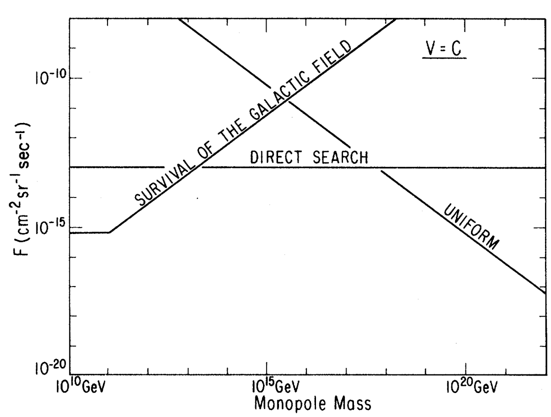

FIG. 3. Same as Fig. 1, except for a monopole velocity of c. The direct-search limit is valid for $v \gtrsim 2\times 10^{-2}c$ and is taken from Refs. 29 and 30. Monopoles with $v \sim c$ cannot cluster with the Galaxy. For a monopole mass of $m = 10^{11}$ GeV, $v \simeq v_{\rm mag}$.

ty, and previous direct searches. In Sec. V we combine the bounds discussed in Secs. III and IV to obtain an upper bound on the galactic flux of monopoles: $F \lesssim 10^{-12}$ cm^{-2} sr^{-1} sec^{-1}. To emphasize the profound implications for astrophysics if a flux $\gtrsim 10^{-12}$ cm^{-2} sr^{-1} sec^{-1} is detected, in Sec. VI we explore two exotic scenarios for maintaining the galactic magnetic field. In these scenarios the flux bound of 10^{-12} cm^{-2} sr^{-1} sec^{-1} can be exceeded because the monopoles themselves are responsible for the field. However, even in these unlikely models the flux is still restricted by the mass density of the Galaxy to be less than 10^{-11} cm^{-2} sr^{-1} sec^{-1}. We conclude by summarizing our results in Sec. VII.

II. THE GALACTIC MAGNETIC FIELD

The magnetic field of the Galaxy is detected through (a) the polarization of starlight,[12] as a consequence of the alignment of the interstellar dust grains[13]; (b) the Faraday rotation measure of polarized radio waves of pulsars and of extragalactic radio sources; and (c) the polarization of the nonthermal (synchrotron) emission from the cosmic-ray electrons.[14] The polarization of starlight shows a large-scale magnetic field extending in the azimuthal direction in the disk of the Galaxy, more or less parallel to the direction of the local galactic arm.[12] Faraday rotation measures indicate a field strength of $(2-3)\times 10^{-6}$ G.[15] There are local fluctuations in the field, with $\Delta B \sim B$, over dimensions of the order of 100 pc (Ref. 16).

Various models of the vertical structure of the galactic disk have been constructed to show that such fields are not inconsistent with the observed state of the cosmic rays and the related nonthermal radio emission, and the observed state of the interstellar gas.[17] Heiles[18] has provided an excellent summary and evaluation of the observations, to which the interested reader is referred. It should be noted that the observations pertain to a volume of space around the Sun with linear dimensions of the order of a kiloparsec.

To obtain a global picture of the galactic magnetic field, one must turn to other galaxies. The Magellanic Clouds (two nearby irregular galaxies) show evidence of magnetic fields.[19] More relevant are the Faraday rotation measures distributed over the spiral galaxies M31, M33, M51, and M81 (Ref. 20). The straightforward interpretation of the observations suggests field strengths of the general order of $(2-5)\times 10^{-16}$ G along the spiral arms. The fields of these galaxies appear to be directed inward along one spiral arm and outward along the other, exhibiting, therefore, a characteristic scale length of the order of 10 kpc. This general picture suggests the conventional view that the locally observed interstellar magnetic field in our own galaxy is part of a large-scale field along the spiral arms, essentially in the azimuthal direction, with a characteristic scale of 10 kpc and a mean field strength of, say, $(2-4)\times 10^{-6}$ G.[18,21]

A central question for estimating an upper limit on the flux of free monopoles in our galaxy is the rate at which the galactic field is regenerated. On the one hand, it has been argued that the present-day galactic magnetic field is a primordial field, having been compressed into its present form along with the collapse of gas that formed the Galaxy. Piddington[22] and Sawa and Fujimoto[23] have explored this theoretical possibility. There would be no regeneration of field, and the characteristic decay time would be comparable to, or greater than, the age of the Galaxy, say 10^{10} yr. On the other hand, Parker[24] has argued that the dynamical instability of the galactic magnetic field and the associated turbulent diffusion produce a characteristic decay time of the general order of 10^8 yr, requiring continual regeneration of the field by dynamo action in the gaseous disk[25] with a characteristic time equal to the decay time if a steady state is to be maintained. Beck[26] discusses the question of a primordial origin of the galactic fields, as opposed to a contemporary production of field, with the conclusion that the observations of the galaxies by themselves provide no definitive answer at the present time. However, Vallee[27] points out that current observations place an upper limit of 3×10^{-11} G on the intergalactic field, as opposed to the earlier suggestion of 10^{-9} G by Sofue, Fujimoto, and Kawabata.[28] A field of 3×10^{-11} G seems to be too weak to provide the observed microgauss fields with the collapse of an intergalactic medium of, say 10^{-5} atoms/cm^3, to form a galaxy. We shall adopt the optimistic point of view, with regard to the abundance of magnetic monopoles, that there is some means of regenerating the galactic magnetic field on a time scale $t_{\rm reg}$ shorter than the age of the Galaxy.

We shall use the following set of parameters as a "working model" for the galactic magnetic field: (a) An average strength of 3×10^{-6} G; (b) a coherence length of 300 pc ($\simeq 10^{21}$ cm), which defines the size of a coherent region, or cell, of magnetic field; (c) a spatial extent of order 30 kpc ($\simeq 10^{23}$ cm) from the center of the Galaxy; and (d) a regeneration time $t_{\rm reg}\simeq 10^{15}$ sec ($\simeq$30 Myr). In addition, we shall assume that the field is largely azimuthal (as the observations indicate). We will use these parameters to derive flux bounds, and will explicitly exhibit how the results scale with these parameters.

III. THE MONOPOLE FLUX AND THE SURVIVAL OF THE GALACTIC FIELD

Monopoles moving through a magnetic field extract energy from the field at a rate equal to $\vec{j}_M\cdot\vec{B}$ causing dissipation of the field energy in a characteristic time $\tau\simeq(B^2/8\pi)/\vec{j}_M\cdot\vec{B}$. If the field can be regenerated in a time as short as 10^8 yr, then the survival of the field requires that $\tau \gtrsim 10^8$ yr. Taking the field strength to be 3×10^{-6} G, this implies an upper bound to a directed flux of monopoles in the galaxy, of the order of

$$F\simeq j_M/4\pi \lesssim 10^{-16}\ \mathrm{cm^{-2}sr^{-1}sec^{-1}}\ . \qquad (1)$$

This is the straightforward bound which has been derived previously.[10,11]

However, we might try to avoid the bound (1) based on this simple argument by assuming that the monopoles are moving through the Galaxy on random trajectories (as they would be if they were gravitationally bound), so that there are as many monopoles gaining energy (by moving in the direction of the field) as there are monopoles losing energy (by moving against the direction of the field). It has been frequently stated that if this were the case, then the survival of the galactic field would place no stringent limit on the monopole flux. Such considerations have motivated our more careful analysis of the situation. In addition, we shall display how the flux bounds which we derive depend upon the precise nature (strength, lifetime, coherence length, etc.) of the galactic field.

A quantity of great relevance in these discussions is $v_{\rm mag}$, the velocity a monopole which is initially at rest would acquire by magnetic acceleration through a region of coherent field. The magnetic force on a monopole of charge $h=69e$ is

$$F_{\rm mag}=hB\simeq 0.06\ \mathrm{eV\,cm^{-1}}B_3\ ,$$

where $B=B_3$ (3×10^{-6} G). The energy gained by the monopole in passing across a field B of scale l_c is

$$\Delta E=hB\,l_c\simeq 0.6\times 10^{20}\ \mathrm{eV}\,l_{21}B_3\ ,$$

where the coherence length $l_c=l_{21}10^{21}$ cm. Therefore, it follows that

$$v_{\rm mag}\simeq 10^{-4}c(\,l_{21}B_3/m_{19})^{1/2}\ , \qquad (2)$$

where the monopole's mass $m=m_{19}10^{19}$ GeV. [Note, if $\Delta E\simeq O(mc^2)$, then (2) is not valid. In this case $v_{\rm mag}\simeq c$.] The significance of $v_{\rm mag}$ is clear. Monopoles with initial velocity $v>v_{\rm mag}$ will be only slightly deflected, i.e., their velocity changes by an amount $|\Delta\vec{v}|$ small compared to their initial velocity, while monopoles with initial velocity $v<v_{\rm mag}$ will be easily deflected when moving through a cell of uniform field, and quickly brought up to a speed of order $v_{\rm mag}$.

We take the monopoles' initial velocity with respect to the Galaxy to be $v\simeq 10^{-3}c$. For if monopoles cluster with the Galaxy or the local supercluster, then their velocity must be of the order of the virial velocity, which for the Galaxy is $10^{-3}c$ ($\simeq$300 km sec^{-1}) and for the supercluster is perhaps as high as $3\times 10^{-3}c$ ($\simeq$1000 km sec^{-1}). On the other hand, if monopoles do not cluster, then they are distributed uniformly throughout the Universe with a velocity dispersion characterized by their present temperature. If they were last in kinetic equilibrium at decoupling ($z\simeq 1500$), then their present temperature would be $\simeq$3 K/1500 (the kinetic temperature of a distribution of noninteracting massive particles $\propto R^{-2}$), which for monopoles more massive than 1 GeV implies a velocity dispersion of $\lesssim$300 cm sec^{-1}. Thus their velocity relative to our galaxy is a consequence of our galaxy's peculiar motion with respect to the cosmic rest frame and their gravitational infall velocity—both of which are $\simeq 10^{-3}c$.

In discussing bounds on the flux of monopoles in the Galaxy there are three cases to be considered: (1) The monopoles cluster with the Galaxy, and $v\sim 10^{-3}c>v_{\rm mag}$; (2) the monopoles do not cluster with the Galaxy, and $v>10^{-3}c>v_{\rm mag}$; and (3) the monopoles do not cluster with the Galaxy, and $v_{\rm mag}\gtrsim v\gtrsim 10^{-3}c$. The case where monopoles cluster with the Galaxy and $v\simeq 10^{-3}c<v_{\rm mag}$ is clearly not a possibility since the monopoles would be quickly accelerated to $v_{\rm mag}$ and would escape from the Galaxy. When we are through analyzing these cases we will have two formulas for the bound on the flux: one valid for $v>v_{\rm mag}$ and one valid for $v<v_{\rm mag}$.

(1) Clustered and $v\simeq 10^{-3}c\gtrsim v_{mag}$. In order for $v\simeq 10^{-3}c\gtrsim v_{\rm mag}$ the monopole mass m must exceed 10^{17} GeV$(l_{21}B_3)$. One can also compare the gravitational and magnetic accelerations of a monopole in the galaxy,

$$a_{\rm grav} \simeq v^2/r \simeq 3\times 10^{-8}\ \mathrm{cm\,sec^{-2}}\ , \tag{3}$$

$$a_{\rm mag} \simeq hB/m$$
$$\simeq 0.6\times 10^{-8}\ \mathrm{cm\,sec^{-2}}(B_3/m_{19})\ . \tag{4}$$

In order that $a_{\rm grav} > a_{\rm mag}$, we must have $m \gtrsim 10^{18}$ GeV B_3. From these considerations it is clear that a necessary condition for monopoles to remain gravitationally bound is $m \gtrsim 10^{17}-10^{18}$ GeV. Shortly, we shall show that if they are to remain bound for a time of order of the age of the Galaxy (10^{10} yr), then $m \gtrsim 10^{19}$ GeV.

Consider the motion of a monopole through a region of uniform field (see Fig. 4). Let its incident velocity be $\vec{v}$ and its velocity as it leaves the region of coherent field be $\vec{v}_f = \vec{v} + \Delta\vec{v}$, where $|\Delta\vec{v}| < |\vec{v}|$ since $v > v_{\rm mag}$. The change in the monopole's energy is

$$\Delta E = m\vec{v}\cdot\Delta\vec{v} + m(\Delta v)^2/2\ . \tag{5}$$

If (a) the distribution of monopole incident velocities is isotropic (as one would expect if they are gravitationally bound), or if (b) the fluxes of monopoles and antimonopoles are equal, then the $h\vec{v}\cdot\Delta\vec{v}$ term averages to zero. We shall assume, then, that for one of these two reasons the $\vec{v}\cdot\Delta\vec{v}$ averages to zero. (In the absence of this assumption, a *more* restrictive bound results.) The average energy gained per monopole due to its slight deflection Δv is then $\Delta E = \frac{1}{2}m\Delta v^2$, where,

$$\Delta v \simeq (hB/m)l_c/v$$
$$\simeq 10^{-5}(10^{-3}c/v)l_{21}B_3/m_{19}\ , \tag{6}$$

$$\Delta E \simeq 2\times 10^{17}\ \mathrm{eV}(10^{-3}c/v)^2 B_3{}^2 l_{21}{}^2/m_{19}\ . \tag{7}$$

ΔE is inversely proportional to both m and v^2. This mean rate of energy gain by the monopoles is just $\Delta E\times$(the number of monopoles which pass through the region per unit time)$\simeq \Delta E\times F\times(4\pi l_c{}^2)\times(\pi\ \mathrm{sr})$. If we require (optimistically) that the field energy of this region, $(B^2/8\pi)(4\pi l_c{}^3/3)$, be dissipated in a time no shorter than $t_{\rm reg}\simeq(10^{15}\ \mathrm{sec})t_{15}$, then the monopole flux bound which follows is

$$F \lesssim 10^{-13}\ \mathrm{cm^{-2}\,sr^{-1}\,sec^{-1}}m_{19}$$
$$\times(v/10^{-3}c)^2 l_{21}{}^{-1}t_{15}{}^{-1}\ , \tag{8}$$

which is independent of the field strength B_3.

Expression (7) for ΔE can be derived in a more rigorous manner. The equation of motion for a monopole in a region of uniform magnetic field $\vec{B}$ is $d\vec{v}/dt = h\vec{B}/m$. Taking the dot product of this

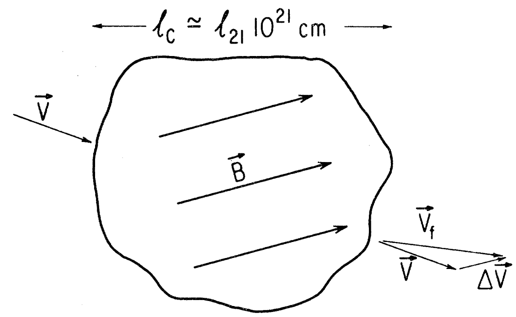

FIG. 4. Schematic representation of a cell (or domain) of coherent magnetic field. For $v \gtrsim v_{\rm mag} \simeq 10^{-4}c(B_3 l_{21}/m_{19})^{1/2}$, a monopole which enters with velocity $\vec{v}$, leaves with velocity $\vec{v}_f = \vec{v} + \Delta\vec{v}$, where $\Delta\vec{v}$ is the small deflection due to the magnetic field.

with $\vec{v}$, it follows that $dT/dt = h\vec{B}\cdot\vec{v}$, where $T = \frac{1}{2}mv^2$. Taking a time derivative and using the equation of motion for $\vec{v}$, we find that $d^2T/dt^2 = h^2B^2/m$, which is necessarily positive. Assumption (a) or (b) implies that $\langle dT/dt\rangle = 0$ when the monopoles enter the field region. The brackets indicate the average over the incident monopole distribution. However, d^2T/dt^2 is always positive so that on average monopoles gain KE, and $\langle T_f\rangle = \langle T_i\rangle + \frac{1}{2}(\Delta t)^2 d^2T/dt^2$, where $\Delta t \simeq l_c/v$ is the time required to traverse the region, $T_i = T(t=0)$ and $T_f = T(t=\Delta t)$. Thus, $\Delta E \simeq \frac{1}{2}(\Delta t)^2 d^2T/dt^2$; it is a simple matter of substitution to show that this agrees exactly with expression (7) for ΔE.

At first it might appear that one could circumvent the flux limit derived above by invoking a special velocity distribution in which the $\vec{v}\cdot\nabla\vec{v}$ term would "balance" against the $(\Delta v)^2/2$ term. We will now illustrate by means of one example that such a "balancing act" is unlikely to be stable. Suppose for the moment that the galactic magnetic field is entirely azimuthal. Consider a monopole configuration with orbits only in the plane of the Galaxy, and for simplicity just one sign of monopole charge. Clearly, with a distribution where half the monopoles orbit clockwise (CW) and the other half orbit counterclockwise (CCW), the net energy gained by the monopoles is zero (half gain energy and the other half lose energy). However, very quickly such a distribution "undoes" itself. The monopoles which are gaining energy, say the CW group, speed up, while the monopoles which are losing energy, the CCW group, slow down. After a while, in a given time interval, the CW group complete more orbits than the CCW group. Since the energy lost or gained in an orbit is just

$2\pi rBh$, the net energy gained by this monopole configuration is no longer zero, but becomes positive. As a rough estimate, the difference in the CW and CCW orbital velocities should grow as $\Delta v \simeq a_{\rm mag} t$. The fractional difference in the number of orbits completed by the CW and the CCW groups should be

$$\Delta N/N \simeq \Delta v/v_{\rm orbit} \simeq 0.2 m_{19}{}^{-1} B_3 t_{15} \; .$$

It seems clear that such a balancing act can work momentarily, but is unstable in the long run.

The $m(\Delta v)^2/2$ term also leads to a steady increase in the average energy per monopole. If the monopoles are to remain bound for a time comparable to the age of the Galaxy $\simeq 3\times 10^{17}$ sec, then the average energy gained in this time interval must not be more than $\frac{1}{2} m v_{\rm escape}{}^2 \simeq 10^{-6} mc^2$. The rate of energy gain due to the deflection term is $\Delta E/\Delta t$, where ΔE is given by Eq. (7), and $\Delta t \simeq l_c/v$ is the time required to traverse a region of coherent field. The long-term stability of the galactic cluster of monopoles therefore requires

$$m \gtrsim 3\times 10^{18} \text{ GeV} (10^{-3} c/v)^{1/2} l_{21}{}^{1/2} \; . \tag{9}$$

(2) Unclustered and $v > 10^{-3}c \gtrsim v_{mag}$. In this case the monopoles will pass through the Galaxy, undergoing just a slight deflection. The analysis for case (1) is also applicable in this situation, and so the bound on the monopole flux is again given by Eq. (8).

(3) Unclustered and $v_{mag} > v \gtrsim 10^{-3}c$. In the very first region of magnetic field that a monopole encounters, it will be accelerated to a velocity of $v_{\rm mag}$. Subsequently, a given monopole will move through the Galaxy, gaining or losing an energy of

$$\Delta E \simeq hBl_c \simeq 0.6\times 10^{20} \text{ eV} B_3 l_{21}$$

in each region of coherent field. A typical monopole transverses a distance comparable to the diameter of the galactic magnetic field region, $2r \simeq r_{23} 10^{23}$ cm, before leaving the Galaxy. During the journey it passes through $2r/l_c \simeq 100 r_{23}/l_{21}$ cells, gaining an energy (on average) of

$$(2r/l_c)^{1/2} hBl_c \simeq 6\times 10^{21} \text{ eV} B_3 (l_{21} r_{23})^{1/2}$$

before it exits. Since its initial energy $\frac{1}{2}mv^2$ is much less than ΔE, the change in its energy as it travels through a given cell, every monopole gains energy while moving through the Galaxy, and on average drains 6×10^{21} eV $B_2(l_{21} r_{23})^{1/2}$ from the energy stored in the field. The flux of monopoles incident on the Galaxy is equal to their flux inside the Galaxy. [Although their average velocity increases v to $\gtrsim O(v_{\rm mag})$, conservation of monopoles requires the flux to remain the same.] Thus the condition for the survival of the galactic field is

$$F\times(\pi \text{ sr})\times(4\pi r^2)\times(6\times 10^{21} \text{ eV} l_{21}{}^{1/2} r_{23}{}^{1/2}) \lesssim (B^2/8\pi)(4\pi r^3/3) t_{\rm reg}{}^{-1} \; , \tag{10}$$

which results in a flux limit of

$$F \lesssim 10^{-15} \text{ cm}^{-2} \text{ sr}^{-1} \text{ sec}^{-1} B_3 (r_{23}/l_{21})^{1/2} t_{15}{}^{-1} \; , \tag{11}$$

where $r = r_{23} 10^{23}$ cm is the size of the magnetic field region of the Galaxy. This result clearly does not depend on whether the incident flux of monopoles is uniform or isotropic

This covers all the possible cases: initial velocity less than or greater than $v_{\rm mag}$ and monopoles clustered or unclustered. The flux bound is independent of m and v for $v < v_{\rm mag}$, and is essentially the original limit which was derived by Parker.[10] For $v > v_{\rm mag}$ the flux limit becomes less restrictive with increasing m and v, because monopoles are less easily deflected. However, it is for larger masses that the bounds on the flux based upon their contribution to the mass density of the Universe and of the Galaxy become more restrictive. We will now discuss these bounds, and then in Sec. V discuss the restrictions on the monopole flux which follow from considering both bounds. The limits on the monopole flux based on the survival of the galactic field are shown in Figs. 1–3 as a function of mass, and for initial velocities of $10^{-3}c$, $10^{-2}c$, and c.

IV. OTHER BOUNDS ON THE MONOPOLE FLUX

The present mass density of the Universe provides an upper bound to the average number density of monopoles. The mass density contributed by monopoles $\rho_M \simeq m_{19} n_M 1.78\times 10^{-5}$ g which must be $\lesssim 2\rho_c \lesssim 4\times 10^{-29}$ g cm^{-3} (for $H_0 \lesssim 100$ km sec^{-1} Mpc^{-1}). This places an upper bound to their average number density $n_M \lesssim 2.2\times 10^{-24}$ cm$^{-3} m_{19}{}^{-1}$ or a flux limit

$$F \lesssim 5.4\times 10^{-18} \text{ cm}^{-2} \text{ sr}^{-1} \text{ sec}^{-1} m_{19}{}^{-1} (v/10^{-3}c) \; , \tag{12}$$

where we have used $F = nv/4\pi$ and, as usual, v is the velocity of the monopoles with respect to the Galaxy. If monopoles are clustered with the Galaxy, then their local density and flux can be significantly greater. If we assume that less than

$10^{12}M_\odot$ of material is within a radius of 30 kpc from the center of the Galaxy, as is indicated by the rotation curve of the Galaxy, then we find

$$F \lesssim 3\times 10^{-13}\ \mathrm{cm^{-2}sr^{-1}sec^{-1}} m_{19}{}^{-1}(v/10^{-3}c)\ . \tag{13}$$

This is consistent with the local density enhancement in the Galaxy being $\sim 10^5$. If monopoles are bound to the Galaxy, then v, their velocity relative to earth, should be ~ 300 km/sec$\simeq 10^{-3}c$. These flux limits are shown in Figs. 1–3.

Previous direct searches for relativistic monopoles ($v \gtrsim 2\times 10^{-2}c$) set an upper limit on the flux of[29,30]

$$F \lesssim 10^{-13}\ \mathrm{cm^{-2}sr^{-1}sec^{-1}},\quad v \gtrsim 2\times 10^{-2}c\ . \tag{14}$$

The interpretation of direct searches for slow monopoles ($v \simeq 10^{-3}c$) is not as straightforward. Such particles are likely to be very lightly ionizing ($v <$ the orbital velocity of electron), and their energy loss in passing through matter is currently a subject of debate.[31] We shall merely summarize, without comment, the published limits[30,32,33]

$$F \lesssim 10^{-10}\ \mathrm{cm^{-2}sr^{-1}sec^{-1}},\quad v \gtrsim 3\times 10^{-4}c\ . \tag{15}$$

These direct-search limits for slow and fast monopoles are indicated in Figs. 1–3. In addition to direct searches, there have been bulk-matter searches[34] which provide a bound on the monopole to nucleon ratio, $n_M/n_N \lesssim 10^{-27}$. They have recently been summarized by Longo,[30] but are not really germane to our discussion of the flux limits.

V. MAXIMUM MONOPOLE FLUX CONSISTENT WITH THE MASS DENSITY AND GALACTIC FIELD LIMITS

From Figs. 1–3 it can be seen that the bounds based on the survival of the magnetic field of the Galaxy become less restrictive with increasing monopole mass and velocity—such monopoles are less easily deflected and spend a shorter time in a region of coherent field. However, the mass density limits become more restrictive with increasing monopole mass. For monopoles clustered with the Galaxy ($v \simeq 10^{-3}c$) these bounds cross at a monopole mass of $\sim 10^{19}$ GeV and a flux of 10^{-13} $\mathrm{cm^{-2}sr^{-1}sec^{-1}}$. Thus, this is the maximum flux permitted for monopoles with typical velocities of $10^{-3}c$. Even pushing their velocity up to the escape velocity for the Galaxy, $v \simeq 3\times 10^{-3}c$, the maximum flux consistent with these two bounds is $10^{-12}\ \mathrm{cm^{-2}sr^{-1}sec^{-1}}$. As we have mentioned earlier, the long-term stability of a distribution of monopoles bound gravitationally to the Galaxy requires $m \gtrsim 3\times 10^{18}$ GeV, and based upon the mass density limit alone the flux is restricted to be $\lesssim 10^{-11}\ \mathrm{cm^{-2}sr^{-1}sec^{-1}}$.

For relativistic monopoles ($v \simeq c$) a flux as large as $10^{-11}\ \mathrm{cm^{-2}sr^{-1}sec^{-1}}$ is consistent with the mass density of the Universe and the survival of the galactic field; however, direct searches rule out a flux of relativistic monopoles greater than $\simeq 10^{-13}\ \mathrm{cm^{-2}sr^{-1}sec^{-1}}$. In sum, a monopole flux $\gtrsim 10^{-12}\ \mathrm{cm^{-2}sr^{-1}sec^{-1}}$ is essentially impossible to reconcile with all the limits we have discussed.

VI. EXAMPLES OF EXOTIC SCENARIOS FOR PRODUCING THE GALACTIC MAGNETIC FIELD

A. Magnetic plasma oscillations

The acceleration of magnetic monopoles in the existing galactic magnetic field produces some interesting mechanical oscillations that bear directly on the question of the existence of the monopoles. To explore the consequences, consider the simple situation in which there is a uniform cold magnetic plasma composed of $\frac{1}{2}n$ monopoles per unit volume with charge $+h$ and mass m, and $\frac{1}{2}n$ with $-h$ and m. Then if $\vec{v}$ is the velocity of the positively charged monopoles as a consequence of their acceleration in a large-scale field $\vec{B}$, it follows that

$$m\, d\vec{v}/dt = h\vec{B}\ , \tag{16}$$

while the velocity of the negative monopoles is $-\vec{v}$. The total monopole current is $\vec{j}_m = nh\vec{v}$. For the simple case of an initial unidirectional field $\vec{e}_x B(x)$, we have $\nabla\times\vec{B}=0$ so that $\vec{E}=0$ and

$$4\pi \vec{j}_m + \partial\vec{B}/\partial t = 0\ . \tag{17}$$

Write $n+\delta n$ in place of n and linearize the equations so that

$$\partial v/\partial t \cong hB/m\ . \tag{18}$$

The result is

$$\partial^2 B/\partial t^2 + \Omega^2 B = 0\ , \tag{19}$$

where the magnetic-monopole plasma frequency is defined as

$$\Omega=(4\pi nh^2/m)^{1/2} . \tag{20}$$

The x dependence of the field is arbitrary, of course. The oscillations are the magnetic analog of the familiar electrostatic plasma oscillations (Langmuir oscillations).

The frequency of the magnetic oscillations is readily computed. For instance, if the monopole flux were 10^{-15} cm^{-2}sr^{-1}sec^{-1} as a consequence of $v=10^{-3}c$, it follows that $n=4\times10^{-22}$ cm^{-3}, while, if F were as large as 10^{-12}, we have $n=4\times10^{-19}$ cm^{-3}. Combined with a mass of 10^{19} GeV (2×10^{-5} g) the oscillation periods are $2\pi/\Omega=4\times10^{8}$ y and 10^{7} yr, respectively. A mass of 10^{17} GeV and a flux of 10^{-15} cm^{-2}sr^{-1}sec^{-1} yields a period of 4×10^{7} yr.

It is evident that the depletion of the galactic magnetic field by free magnetic monopoles, described in the earlier sections, is nothing more than the first quarter cycle of a galactic monopole plasma oscillation, converting the energy of the magnetic field into kinetic energy of the magnetic monopoles. For $n=4\times10^{-22}$ cm^{-3} this amounts to 5×10^{11} GeV/monopole, equivalent to a velocity of $0.3\times10^{-3}c$ for a rest mass of 10^{19} GeV, etc.

A coherence length $l=10^{21}$ cm for the field gives a phase velocity $l\Omega/2\pi$, equal to $10^{-4}c$ for a period of 10^{7} yr and $10^{-5}c$ for 4×10^{8} yr. This phase velocity is less than the expected random velocities of the indiviual monopoles, so that, in fact, the galactic monopole plasma, if it exists, would not be cold as we have assumed in the foregoing sections. The point is that the oscillations are subject to strong Landau damping, which disperses the energy in one period of the oscillation, or less. Thus, we end with the same quantitative conclusion as before, that the monopole density or flux must be severely limited [as described by (8) and (11)] if the observed magnetic field, with an assumed characteristic regeneration time of at least 10^{8} yr (3×10^{15} sec), is to survive.

We could go on to pursue some of the transverse electromagnetic modes in a combined magnetic and electric plasma. We could consider the consequences of the phase incoherence that arises from the spatial variation of the monopole density and the associate monopole plasma frequency. It is obvious that the gravitational field should be included in the calculations, providing further new modes of excitation. The consequences of the magnetic oscillations for the galactic cosmic rays trapped in the magnetic field are considerable, of course. It is an interesting exercise to formulate the hydromagnetic equations in the presence of free monopoles and to work out the familiar dynamo equations, so that the field grows in amplitude at the same time that it oscillates. But we feel that the uncertainties in the existing monopole density do not warrant publication of further investigations at the present time.

B. Radial galactic field

Another exotic possibility for creating and maintaining the galactic magnetic field that immediately comes to mind is that a net galactic magnetic charge is responsible for the field. For a simple estimate, let the excess number density of plus poles over minus poles be n, and assume that n is constant. Then at a distance of ~10 kpc (3×10^{22} cm), $B\simeq(4\pi/3)nhr$, which is 3×10^{-6} G for $n=10^{-21}$ cm^{-3}. This corresponds to a net magnetic charge within 30 kpc of the center of the Galaxy of $\sim4\times10^{48}$ h. Since this is the excess of plus poles over minus poles, this sets a *lower* bound on the flux of

$$F\simeq3\times10^{-15}\ \text{cm}^{-2}\text{sr}^{-1}\text{sec}^{-1}(v/10^{-3}c) .$$

If monopoles are the primary sources of the galactic field, then $\nabla\times\vec{B}=0$ and the field is conservative, i.e., the energy gained by a monopole traversing a closed path through the field is zero. The field energy cannot be dissipated without neutralizing or dispersing the net magnetic charge since it is a consequence of Gauss's law. However, the field is *radial,* and as we discussed earlier, there is very good evidence that the galactic field is mainly azimuthal. Maxwell's equations imply that an azimuthal field must be maintained by currents which, of course, can be dissipated. There is also the question of how the magnetic charge imbalance would arise and continue to exist. If it is just statistical, then a net charge of $\sim10^{48}$ requires the number of plus and minus poles to be $\sim10^{96}$, or a flux of $F\simeq10^{33}$ cm^{-2}sr^{-1}sec^{-1}, which is clearly ridiculous. If the Galaxy had such a net magnetic charge, it would attract monopoles of the opposite charge from the intergalactic medium or from other galaxies to neutralize its charge.

In either exotic scenario, the monopoles must be gravitationally bound to the Galaxy, so that their magnetic interactions do not cause them to disperse. This, as we have discussed previously, requires the monopole mass m to exceed $\sim10^{18}$ GeV. Based on the mass density limit alone, Eqs. (12) and (13), the monopole flux can be no greater than 10^{-11} cm^{-2}sr^{-1}sec^{-1} if $m\gtrsim10^{18}$ GeV. So even by considering these very unlikely schemes, we have only relaxed the limit discussed in Sec. V ($F \lesssim 10^{-12}$ cm^{-2}sr^{-1}sec^{-1}) by an order of magnitude.

VII. SUMMARY AND CONCLUSIONS

The simplest arguments based upon the survival of the galactic magnetic field[10,11] limit the monopole flux to be $F \lesssim 10^{-16}$ cm^{-2}sr^{-1}sec^{-1}. In our more detailed analysis we have found the flux bounds in two limiting regimes: (i) for v (initial monopole velocity) $< v_{\rm mag} \simeq 10^{-4} c (B_3 l_{21}/m_{19})^{1/2}$ (monopoles are easily deflected by the galactic field),

$$F \lesssim 10^{-15}\ {\rm cm}^{-2}{\rm sr}^{-1}{\rm sec}^{-1} B_3 (r_{23}/l_{21})^{1/2} t_{15}{}^{-1}\ ,$$

which is essentially the same as the previous result; and (ii) for $v > v_{\rm mag}$ (magnetic deflection is only a perturbation to their motion),

$$F \lesssim 10^{-13}\ {\rm cm}^{-2}{\rm sr}^{-1}{\rm sec}^{-1} m_{19} (v/10^{-3}c)^2 \times (t_{15} l_{21})^{-1}\ .$$

These limits do not depend on whether the velocity distribution of the monopoles is uniform or isotropic. Here B_3, l_{21}, t_{15}, and r_{23} parametrize the field strength, $B = B_3 3\times 10^{-6}$ G, the coherence length $l_c = l_{21} 10^{21}$ cm, the optimistic regeneration time $t_{\rm reg} = t_{15} 10^{15}$ sec for the galactic magnetic field, and the extent of the field region, $r = r_{23} 10^{23}$ cm. While m_{19} and v specify the monopole's mass, $m = m_{19} 10^{19}$ GeV, and typical velocity with respect to the Galaxy. These limits together with the restrictions derived from the average mass density of the Universe and of the Galaxy place stringent bounds on the flux of monopoles in the Galaxy (see Figs. 1–3). For example, with $v \simeq 10^{-3}c$, the maximum permissible flux is $\sim 10^{-13}$ cm^{-2}sr^{-1}sec^{-1}, which is allowed for monopoles of mass $m \simeq {\rm few} \times 10^{19}$ GeV which cluster with the Galaxy. If we allow v to be $3\times 10^{-3}c$ ($\sim$ escape velocity for the Galaxy), and still assume that such monopoles cluster with the Galaxy, the flux could be as large as 10^{-12} cm^{-2}sr^{-1}sec^{-1}. Although the flux bounds based on magnetic fields discussed here are less restrictive than those previously derived,[10,11] there is no way to reconcile a flux $\gtrsim 10^{-12}$ cm^{-2}sr^{-1}sec^{-1} with the survival of the galactic field. In fact, the requirement that monopoles which cluster with the Galaxy remain bound for the age of the Galaxy requires that $m \gtrsim 3\times 10^{18}$ GeV, and, based upon their mass density alone, this restricts the flux to be $\lesssim 10^{-11}$ cm^{-2}sr^{-1}sec^{-1}.

Of course, these bounds only apply to the average flux in the Galaxy and do not preclude, *per se*, local sources.[35] However, local sources are not without their difficulties. For example, consider the possibility that monopoles are produced by cosmic-ray interactions in the atmosphere. The integrated flux of cosmic rays with energy greater than 10^4 TeV is $\simeq 10^{-12}$ cm^{-2}sr^{-1}sec^{-1}. The center-of-mass energy for a 10^4-TeV particle colliding with an oxygen nucleus in the atmosphere is ~ 16 TeV. Thus the cosmic ray produced flux of monopoles more massive than ~ 10 TeV must be less than $\sim 10^{-12}$ cm^{-2}sr^{-1}sec^{-1}.

A monopole flux of 10^{-12} cm^{-2}sr^{-1}sec^{-1} is essentially impossible to reconcile with the present mass density of the Galaxy and our understanding of the magnetic field of the Galaxy. If such a flux is, or already has been detected,[8] and is not a local phenomenon, then in addition to the profound consequences for particle physics and for cosmology, there are equally profound implications for our understanding of large-scale magnetic fields.

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