Future Search for Grand Unified Theory Magnetic Monopoles

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Abstract

After a brief discussion of the theoretical notation, we discuss the present experimental limits and experimental techniques in the search for very massive magnetic monopoles. We attempt to survey possible future experiments and the limits of the experimental techniques with emphasis on the type of R and D that will be useful in these searches.

Outline

1. Introduction and Brief Theoretical Introduction
2. Present Limits on Cosmic Monopole Flux
3. Monopole Interaction with Matter
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5. Search for Monopoles in Very Old Material
6. R and D on Detection of Monopoles - Future Searches

1. Introduction

The symmetry between electric fields and magnetic fields in Maxwells equation, and lack of abundant free magnetic charge compared to electric charge has captured the attention of several generations of physicists. In 1931 Dirac went one step further, the existence of free magnetic charge (Dirac Monopole) can provide a reason for the quantization of electric charge (e.g.=nh/c)[1]. A preview of the Dirac formula was provided earlier by J.J. Thompson who discussed the quantization of the electromagnetic field, (values of nh/c can be shown to give the Dirac condition). Many distinguished scientists have worked on the monopole problem in the intervening years. It is notable that there was never a convincing argument in favor of a particular mass of the Dirac monopole. Experimental searches were shooting in the dark. In 1974 t'Hooft and Polyakov showed that magnetic monopoles exist as solutions in many Non Abelian gauge theories (including Grand Unified Theories)[2]. This theory provides a mass scale for the monopole related to the vector bosons in the gauge theory at the mass values of ~13 TeV or 10^{16} GeV.[2] The interest in this subject has grown in the past few years. One of the striking features of unified theories of weak and electromagnetic interactions and of the Grand Unified interaction is that relations between masses, mixing angles and coupling constants are derived[2]. For example, the mass of the intermediate bosons follow from the Weinberg angle and the Fermi coupling constant G. The first concrete prediction of the monopole mass came from reference[2].

$$M_m \simeq (\alpha)^{-1} M_W \simeq 13 \text{ TeV} \qquad (1)$$

In models of weak electromagnetic unification. However, the success of QCD and remarkable similarity of the weak, electromagnetic and strong interaction has lead to the concept of Grand Unification. In this case the unifying mass is the mass of X, Y lepton-quark bosons. The corresponding monopole mass is now expected to be

$$M_m \simeq (\alpha)^{-1} m_X \simeq 10^{16}\text{–}10^{17} \text{GeV} \qquad (2)$$

since it is thought that Mx $\sim 10^{14}$–10^{15}GeV. The large masses "predicted" for the magnetic monopole immediately change ones evaluation for the previous searches for monopole for two reasons:

1. The experimental signature or production yield in cosmic ray interactions for a 13 TeV or 10^{16}–10^{17} monopoles is likely to be different from that expected for light and hence very

relativistic monopoles - this had been one of the key signatures for monopoles in the cosmic rays.

2. The production rate of such massive monopoles in cosmic ray interaction (α 13 TeV) or the early universe (10^{15}-10^{16}) GeV is unpredictable. Fig. 1 shows the standard scenario for the early expansion of the Universe and the period when the monopoles were presumed to be produced[3].

There are constraints on the number of free magnetic charges in the Galaxies due to the existance of galactic magnetic fields or on the number of particles in the universe with very high mass (due to the total amount of mass in the universe). These constraints limit the number of monopoles to a small fraction of the number of nucleons and immediately lead to, at best very small fluxes of monopoles in the cosmic radiation.[3,4,8]

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1.1 Magnetic Monopoles: Theoretical Introduction

Magnetic monopoles, like baryon-number violating nucleon decays, are a natural prediction of grand unified theories (GUTS). Both result from the essential underlying idea of grand unification: that quarks and leptons transform as members of the same (irreducible) representations of a simple gauge group, G. The local G-symmetry must be broken and eventually yield a U(1) factor group; i.e. it is necessary that $G \to H \times U(1)$. In realistic theories, this U(1) contains an electromagnetic part. A topological consequence of this breaking pattern is that the theory will contain magnetic monopoles.[4] Such theories make definite predictions for the magnetic and electric charges, masses and other quantum numbers of these monopoles. In particular, as will be discussed later, the minimally charged monopoles also carry color magnetic charge and are generally quite heavy, with masses of order $\alpha^{-1} m_{GU}$, where m_{GU} denotes the grand unification mass scale ~ 10^{14}GeV. These properties have important implications for the planning of monopole search experiments. Of course, it should be stressed, that just as in the case of neutrino masses, lepton number violation and $n-\bar{n}$ transitions, the existence of monopoles is a general phenomenological possibility, independent of grand unification. But, monopoles, like proton decay and unlike the latter phenomena, are a relatively firm feature of GUTS. Before proceeding to discuss GUT monopoles further, it is instructive to recall some developments in the theory of magnetic monopoles.

In 1931, requiring that the quantum mechanical wavefunction of electrically charge particles be single-valued, Dirac[1] derived a simple quantized relation between electric and magnetic charge, q and m

$$qm=n/2, \quad n=0, \pm 1, \pm 2 \ldots \qquad (3)$$

This elegant result was very appealing, since it could explain the observational fact that electric charge is quantized. The existence of even a single magnetic monopole with m=1/2e would explain why electric charge is always quantized in units of e. (It should be noted that in the framework of GUTS both charge quantization and the existence of magnetic monopoles are consequences of the simple compact group underlying the theory).

The Dirac theory provided strong motivation for magnetic monopole searches, but gave little quidance regarding their physical attributes. They were expected to be point like objects with magnetic charge of magnitude 137ne/2, but their masses were undetermined. The classical field configuration of a point magnetic monopole has infinite rest energy because of the $1/r^2$ singularity in its radial magnetic field. (The same kind of infinity occurs for a point electric charge.) If a self-consistent quantum field theory of Dirac monopoles existed, it might circumvent this problem through renormalization, but the monopole mass would remain arbitrary. Traditional searches for magnetic monopoles have generally fallen into two categories. The first category consists of ionization experiments which search for magnetic tracks. If monopoles are relativistic, they should leave broad, even tracks as they pass through matter; these would be easily distinguished from the broadening tracks of a highly charged ion. The second type of experiment measures the magnetic charge of materials in which monopoles might have accumulated, such as iron ore, ocean sediments, moon rocks, etc. Neither method has produced any accepted magnetic monopole candidate.

The theory of magnetic monopoles underwent a renaissance in 1974 due to the work of 't Hooft[5] and

Polyakov[6]. They independently pointed out that theories based on simple, compact, non-abelian gauge groups which are realistic i.e. break in such a way as to leave a residual exact $U(1)_{em}$ factor group, necessarily contain magnetic monopoles. As was mentioned before, such theories automatically exhibit electric charge, quantization because of the compact nature of the covering simple gauge group which contains the $U(1)_{em}$. Thus, both the existence of magnetic monopoles and electric charge quantization arise from the topological properties of simple compact groups in the more modern viewpoint. A further interesting feature of the ´t Hooft-Polyakov magnetic monopoles was that they had predictable masses, which were finite, at least at the classical level. The field configurations found in Ref. 5 and 6 were finite energy solutions to the classical Euler-Lagrange field equations. They were stabilized by the nontrival topology of the Higgs scalar field configuration for those solutions. Thus magnetic charge was found to be associated with topology rather than with conserved Nocther currents. The Higgs scaler fields which were introduced to break the gauge symmetry and provide masses for the intermediate vector bosons in non-abelian gauge theories also led to finite energy magnetic monopoles. The mass of the monopole was proportional to the Higgs vacuum expectation value which for the SO(3) model considered implied $m_M > 10$TeV. This was the first indication that magnetic monopoles may be very massive.

The magnetic monopole field configurations discovered by ´t Hooft and Polyakov for an SO(3) model are not so unusual. They occur in any compact non-abelian gauge theory based on a simple group which breaks down to a smaller subgroup containing a U(1) generator. Furthermore, the appearance of finite energy classical solutions in non-linear field theories is a well know phenomenon in condensed matter physics. Magnetic vortices in type II superconductors and point defects in liquid crystals are two such effects. (There are a host of others.) Analogous to those configurations, the ´t Hooft-Polyakov monopole is not completely point-like. It exhibits structure at very short distances $1/m_M$.

The standard model breaks down to $SU(3)_c \times U(1)_{em}$ via a Higgs mechanism; but it does not (by itself) accommodate ´t Hooft-Polyakov monopoles because the theory starts out with a semi-simple covering group, $SU(3)_c \times SU(2)_L \times U(1)$. However, in 1974 GUTS also emerged. It was shown by Georgi and Glashow[7] that large simple gauge groups quite naturally contain the $SU(3)_c \times SU(2)_L \times U(1)$ model. For example, the SU(5) model has a two step Higgs mechanism.

$$SU(5) \xrightarrow[m_{GU}]{} SU(3)_c \times SU(2)_L \times U(1) \xrightarrow[m_W]{} SU(3)_c \times U(1)_{em} \tag{4}$$

The first step at $m_{GU} \simeq 10^{14} \sim 10^{15}$GeV takes one from a simple compact group to a subgroup with a U(1) factor and thereby leads to ´t Hooft-Polyakov monopoles with $m_M \simeq 10^{16}$GeV. This pattern of symmetry breaking is a general feature of grand unified models; thus, magnetic monopoles are a natural consequence of GUTS.

The possibility of very massive monopoles may create a problem for naive big bang cosmology[8]. Within the framework of that theory such monopoles should have been copiously produced at high temperatures during the very early universe ($t \simeq 10^{-35}$sec.) and should still be abundant. Crude estimates[9] suggest that the number of super-heavy monopoles presently in the universe should roughly equal the number of baryons$\simeq 10^{80}$. However, if that were the case, their large mass would lead to gravitational collapse of the universe at a tremendous rate. Bounds on the contraction rate imply (for $m_M = 10^{16}$GeV).

$$n_M/n_B < 10^{-14} \tag{5}$$

The need to suppress the number of super-heavy monopoles by 14 orders of magnitude is often referred to as the "monopole problem" of GUTS. Is there really a problem? That question is still somewhat controversial.[9] (One doesn´t reliably know monopole production cross-sections or what may have happened during the early evolution of the universe.) Assuming that there is, indeed, a problem, various authors have proposed possible remedies, which, however, often involve considerable complication of the theory.

Not worrying about possible cosmological problems, one may ask: How might remenant super-heavy monopoles be detected? Their large mass combined with the adiabatic expansion of the universe should have rendered them quite non-relativistic, with $\beta = v/c \simeq 10^{-3} \sim 10^{-4}$. It then follows that ionization tracks may not be a feasible way to detect such monopoles. (There is at present some disagreement concerning the ionization properties of slow moving monopoles.[10]). Furthermore, their large momentum and gravitational attraction suggest that they may not be trapped in materials where traditional searches have been carried out. In any case, the tentative observation by Cabrera[11] of a magnetic monopole using a squid (superconducting quantum interference device) flux loop has caused considerable excitement. As a result, new experiments using larger squids, scintillators etc. are already underway or being planned. (These will be described later.) There is of course considerable skepticism regarding the interpretation of Cabrera's event as a magnetic monopole. Indeed, if one were to assume a uniform cosmic magnetic monopole flux[12], that one event would correspond to a flux 10^4 times larger than the upper limit imposed by the constraint of persistence of the galactic magnetic field[14].

We conclude this theoretical introduction by outlining the expected properties (some still speculative) of 't Hooft-Polyakov monopoles in the simplest SU(5) model.

SU(5) Magnetic Monopoles[14]

1. Magnetic Charge: GUT monopoles can carry $SU(3)_c \times SU(2)$ and U(1) magnetic charges. Projecting out the $U(1)_{em}$ component, one finds that monopoles with m=1/2e (the Dirac unit) must also carry color magnetic charge. Colorless monopoles carry magnetic charge which is a multiple of 3/2e. Those monopoles carrying color magnetic charge presumably have their color fields screened by gluons; so it is not long range. However, they should still undergo residual strong interactions with hadronic matter. Those strong interactions are not yet fully understood; they may provide a way of detecting monopoles.

2. Mass: The lightest SU(5) monopole has m=1/2e and carries color magnetic charge. Its mass is expected to be $\approx 10^{16}$GeV. All higher charged monopoles are likely to be unstable. They would decay into several of the lightest ones.

3. Dyons: Electrically charged magnetic monopoles have been denoted as dyons by Schwinger.[15] Quantizing the SU(5) model, one finds that dyons arise as quantum excitations of monopoles. The dyon states generated in this manner carry electric charge $q_n = n(-4/3)e$ and transform like a symmetric product of n $\underline{3}$ representations of $SU(3)_c$ i.e. they can carry ordinary color charge. Furthermore, they have a B-L quantum number equal to n(-2/3). These dyons are heavier than sure magnetic monopoles by about n x 10^{12}GeV.

4. Baryon Decay Catalysis: It was pointed out by Dokos and Tomaras[14] and by Rubakov[16] that monopoles may catalyze baryon decay.

$$p + M \rightarrow e^+ + M + X \qquad (6)$$

The first set of authors conjectured that the cross-section was suppressed by $1/m^2_{GU}$. A much larger rate was obtained by Rubakov viz. $\sigma \approx 10^{-26}cm^2$! Callan has recently presented arguments in favor of this larger rate[17]. Needless to say, considerable theoretical uncertainty regarding baryon decay catalysis by monopoles presently exists. This uncertainly makes it difficult to derive upper bounds on terrestrial monopole fluxes from proton decay experiments or upper bounds on cosmic monopole fluxes from considerations of baryon decay catalysis in neutron stars.[18] This topic will be further discussed in a later section of this report. It joins together two exciting possibilities, proton decay and magnetic monopoles. The detection of either would be a great discovery.

2. Limits on Cosmic Monopole Flux

2.1. The Acceleration of Monopoles in Galactic Magnetic Fields

The calculation of the acceleration of massive monopoles on the galactic magnetic field is subject to many uncertainties including the effects of gravitation (since the gravitational and magnetic forces are comparable) and the actual size of the galactic magnetic fields. It seems clear that low velocity monopoles that are gravitationally bound will have trajectories that are frequently orthogonal to the direction of the magnetic field and therefore experience no net acceleration from the magnetic field. The rough range of velocities expected for various mass monopoles is shown in Fig. 2. Various kinds of indirect limits on the flux of monopoles that have been reported are also shown in Fig. 2. Generally, these limits are much lower than the flux implied by the single event in the Cabrera experiment. However, for velocities below $\beta = 10^{-3}$ the only model independent limit comes from the density of matter in the universe or from constraints implied by the existence and properties of galactic magnetic fields. In order to apply these limits to any one part of the universe it is necessary to assume a uniform density and of course in principle our galaxy may have an accidental large fluctuation of magnetic monopoles. Recently Turner, Parker and Bogdon[20] have refined the previous Parker Bounds. These new bounds are shown in Figure 3. Unless monopoles are trapped in the local environment, these bounds are very restrictive on the flux of cosmic monopoles.

2.2. Present Limits on the Abundance of GUT Monopoles

We summarize here the best current limits on the abundance of primordial GUT monopoles. Since these objects are assumed to have masses $\sim 10^{16}$GeV, we will not be concerned with limits on the production of light monopoles at accelerators or by cosmic rays. Table 1 lists some representative limits which have been calculated from different types of astrophysical observations, which preclude the existence of monopoles above some level in particular locations, within the content of a cosmological model. For example, monopoles should not be so abundant that they dominate the mass of the universe,[19] or run down the observed magnetic fields of the galaxy,[20,21] the earth[22,12] or the sun.[23,24] While the monopole flux implied by the Cabrera event[25] is apparently much too large to be representative of the average flux in the universe or even in the galaxy, it could still be due to a local concentration of monopoles in the solar system.[23,24]

There is growing acceptance of the idea that GUT monopoles should catalyze proton decay at some level,[18-27] although there is still considerable uncertainty over the magnitude of the cross section for this process. This mechanism allows the lack of evidence for proton decay to be interpreted as a limit on the abundance of monopoles. Assuming that monopole catalysis of proton decay has a typical strong interaction cross section, Kolb et al.[18] have calculated the flux of x-rays to be expected from nucleon decays in neutron stars, a particularly efficient site for monopole catalysis to occur. Ellis et al.[26] have also assumed the strong interaction cross section, and have calculated the flux of monopoles incident on proton decay experimental limits. The theoretical investigation of monopole-catalyzed proton decay is still in its initial stages, and we can expect considerable future refinements of the limits given in Table 1.

Table 2 summarizes the experimental limits on GUT monopole abundances which have resulted from direct laboratory measurements. The limits from stable matter searches[28,29] are among the most restrictive, but are subject to the rather uncertain binding properties of very heavy monopoles to matter[19]. It seems likely that only ferromagnetic materials have any hope of retaining monopoles securely in the presence of even modest mechanical accelerations in the host material. This may make the limits from iron-bearing moon rock and meteorites[28,29] particularly meaningful.[19]

It is difficult to invent mechanisms for accelerating GUT monopoles to velocities greater than 10^{-3}c. Thus, in contrast to the pre-GUT expectations for light, heavily ionizing monopoles, we now believe that GUT monopoles will ionize rather lightly, if at all. Nevertheless, some rather good limits on the flux of very heavily ionizing objects have been obtained, and the best of these[29] is quoted in Table 2. The most restrictive direct limits on monopole fluxes come from the Baksan experiment.[31] Since this limit is the result of only 135 days of operation, a substantial improvement can be expected with longer operation. The 1800 m^2sr acceptance of the Baksan facility will not be easily exceeded by future detectors. Scintillator excitation has a lower threshold energy than argon gas, and so the scintillator searches[31-33] listed are potentially sensitive to lower monopole velocities (dE/dx) than searches requiring ionization in argon.[34,35]

3. Monopole Interactions with Matter

3.1. Interaction of Monopoles with $\beta > 10^{-3}$

Monopoles interact with matter by their magnetic field $\vec{B}_M = g\hat{r}/r^2$.[41,42] The force on a nearby electron (or nucleus) has two components. There is an electric force $\vec{E}_e = q\vec{\beta} x \vec{B}_M$ due to the Lorentz-transformed magnetic field in the electron rest frame. There is also a magnetic force $\vec{F}_M = (\vec{\mu} \cdot \vec{\Delta})\vec{B}$ due to the interaction with the electron's magnetic moment. Since $g = e/2\alpha \simeq 68e$, the force F_e would result in a large ionization loss for a relativistic monopole, roughly comparable to that for a relativistic Z=68 nucleus. Geer and Scott have calculated S for slow monopoles in atomic hydrogen ($\beta > .01$). Ahlen and Kinoshita have recently carried out a rather complete calculation of the stopping power for magnetic velocities down to $\beta \sim 10^{-4}$, Figure 4 shows their results.[10] It seems clear that scintillation counters can be used to detect monopoles with $\beta > 10^{-3}$. There already exists a very large scintillation detector (1800 m^2sr) at the Baksan laboratory in the USSR.[30] This detector has been used to search for monopoles with $\beta > 10^{-3}$ in the past few months.[30] (See Fig. 2)

The ionization energy loss of charged particles at low energy in solids has been studied first by Fermi and Teller.[40] For a degenerate electron gas the energy loss is given by:

$$-\frac{dE}{dx} = \left(\frac{2Z^2 e^4 M_e^2 c}{3\pi h^3}\right) \beta \ln \left(\frac{\beta_F}{\alpha}\right) \qquad (7)$$

where $\beta_F = CV_F$, where V_F is the Fermi velocity ($\sim 10^3$ Km/sec). Only electrons whose velocity satisfy

$$v_F - v < v_e < v_F \qquad (8)$$

contribute to the collision. This picture has recently been extended to the stopping power of monopoles at low velocity. The calculations of Ahlen and Kinoshita are an example (Figure 4). Note the rapid falloff of the ionization at very low velocity and uncertainty in the various calculations. Detection efficiency is a function of the type of detector used at a given monopole velocity. Figure 5 shows an estimate of the scintillation light yield using thee same calculation.

3.2. Low Velocity Interactions with Matter

The most common magnetic monopole detectors such as scintillator or proportional tubes use the monopole´s excitation of atomic electrons to detect its passage. The amount of energy transferred to the atomic system must be above the threshold desired, a few eV for scintillator or about 10 eV for a gas counter. A lower limit on the energy a monopole can transfer to the atomic electrons may be calculated by considering the electric field of a monopole moving with respect to the electrons in the detector interacting with those electrons. This type of calculation of electronic stopping power ignores the possibly more important effects of proton decay catalysis, accretion of charged particles, strong interactions, elastic collisions with atomic nuclei and magnetic field interactions with the electrons´ magnetic moment. Naively the electronic stopping power for a monopole will be the same as that for a charged particle with the charge of the particle replaced by the monopole magnetic charge, g, times the Lorentz factor which depends on the relative velocity of the monopole and atomic electrons, $\gamma\beta$. A schematic plot of the electronic energy loss of a proton is given in Figure 6a. For a Dirac monopole $g = \frac{e}{2\alpha}$, so that fast monopoles transfer a great deal of energy to the atomic system. Detection problems arise only for small monopole velocities.

The speed of the earth in its orbit around the sun sets a lower limit for the speed of a significant fraction of monopoles colliding with a detector. Thus $\beta = 10^{-4}$ is the lowest monopole velocity which need be considered. For charged particles, the electronic stopping power is well represented by the techniques used by Lindhard and coworkers.[46] This approach uses Maxwells equations and a degenerate electron sea to predict an energy loss which is linear with the velocity of the charged particle for $\beta < 10^{-2}$. Data are in good agreement with the Lindhard model for $\beta > 5 \times 10^{-3}$. For smaller speeds, data is sketchy and in some disagreement. In addition measured charged particle energy loss begins to be dominated by other effects such as nuclear collisions energy loss and screening due to electron capture by the projectile. For a review of the charged particle situation see Wu[37] and Janni.[38]

Ahlen and Kinoshita[39] have applied the Lindhard approach to the electronic interaction of monopoles through matter and derived the same linear β dependence as for charged particles. In the same paper they also apply the Fermi-Teller approach to the problem using a monopole cross-section of Kazama, Yang and Goldhaber[43] with similar results. Ritson[41] then took the Ahlen and Kinoshita results and applied them to the case of real materials by using measured proton energy loss at $\beta = 5 \times 10^{-3}$ to evaluate the common behavior of protons and monopoles.

His formula for $g = \frac{e}{2\alpha}$,

$$\left.\frac{dE}{dz}\right)_{monopole} > \frac{1}{4} \left(\frac{\beta}{5 \times 10^{-3}}\right) \frac{\bar{V}_f^2}{\alpha^2 c^2} \left(\frac{dE}{dz}\right)_{proton} \qquad (9)$$

has z in gm/cm^2 and $\bar{v}_f^2$ as the effective fermi velocity of electron sea calculated taking into account the energy gap of the detector. For carbon and argon Ritson uses 240 and 75 times minimum ionizing respectively for $\left.\frac{dE}{dz}\right)_p$. This difference makes carbon a more effective detector by a factor of 3. Using the appropriate energy gap for the two materials causes the calculated electronic stopping power to decrease and faster than β for $\beta < 10^3$. However the result is not very sensitive to the actual energy gap size. Ritson's graphs are reproduced as Figures 6b and 6c.

The Lindhard model as applied by Ahlen and Kinoshita and then by Ritson implies that conventional detectors of scintillator or even gas ionization will be appropriate to search for magnetic monopoles. However, for $\beta < 3 \times 10^{-4}$ the signal size would be marginal within the assumptions of the model. Before large expensive detectors are built to search for monopole fluxes at the expected levels it would be comforting to invest some effort in a computer simulation of the quantum mechanics a slow, $\beta \approx 10^{-4}$, monopole passing through a material of descrete atoms or molecules.

3.3. Detection of Monopoles by Flux changes in Superconducting Coils

In the pioneering experiments of the Alvarez group monopoles were searched for using small superconducting coils.[27,28] The use of a SQUID magnetometer to search for magnetic monopoles was one of the earliest applications of the SQUID, and the technique has since been further refined. It is inherently appealing because the passage of a single monopole through a superconducting circuit would produce a flux change of two quanta ("fluxons"), while the output of a SQUID is periodic in flux with a period of one fluxon (2×10^{-15} Weber). Hence as long as the noise level can be kept sufficiently low, the passage of a monopole through a superconducting coil magnetically coupled to a SQUID should give a large, unique, and unmistakable signal, a DC level shift of two periods. SQUID magnetometers now commercially available are sensitive at the millifluxon level. Thus SQUID-based monopole detectors operate in a regime in which sensitivity can actually be sacrificed in the interest of noise reduction.

Nonetheless, in a magnetometer designed to admit a material sample, the noise problem can be quite severe. As a benchmark, it should be noted that the Earth's magnetic field amounts to about a million fluxons per square centimeter. Thus previous monopole searched by this technique have utilized coils with apertures of less than a square centimeter, and have accordingly been restricted to the study of very small samples, with an aggregate mass of a few tens of grams.

The detectors can be divided up into those that are used to search for Cosmic Monopoles ($\beta > 10^{-4}$) and those that are used to search for monopoles bound to matter or released from matter in the earth's gravitational field ($\beta \ll 10^{-5}$). An example of the former detector is the one used by Cabrera (Figure 8) in which extremely low magnetic fields were maintained by the use of inflated super conducting lead "balloons". This detector needs to be rather isotropic in order to increase the solid angle for cosmic monopoles.

But a search for monopoles with masses comparable to the Grand Unification scale, in free fall in the earth's gravity, invites the use of a very different sort of magnetometer. Such objects, with or without a "retinue" of bound atoms, can freely penetrate ordinary solids. Even superconductors are penetrable, for as a monopole approaches a superconducting surface, its field surpasses the superconductor's critical field long before forces capable of having a significant effect on its motion have been generated. Furthermore, the origin (at least the point of origin) of these monopoles is known and thus the angular acceptance can be increased and the requirements of extremely low magnetic fields can be relaxed. Furthermore, several coils can be put in coincidence. This is the technique used for the Wisconsin monopole detector.[36] (Figure 9)

We now discuss the size limitation of superconducting coil detector the largest SQUID magnetometer built to date were experimental antennas for VLF radio reception by submarines. Their apertures approach a square meter. They differ from the device needed for monopole detection in two important respects: first, they are coupled to the SQUID through a resonant system of modest bandwidth, tuned to a 3 KHz carrier; second, magnetic shielding was restricted to a conductive layer to damp out high-frequency eddy currents, plus the natural shielding provided by seawater.

A new DC SQUID is being developed by SHE Corp. Using this SQUID, it should be possible to construct superconducting monopole detectors with a diameter of 1m or more. This seems to be the limitation size for the near future.

3.4. Monopole Binding to Nuclei and in Matter

There have been several calculations of the binding energy of a magnetic monopole near a domain boundry. Inside 300 Å, the field exceeds the interior magnetic field of a domain, and at distances of less than 100 Å, the field exceeds the saturation fields of ferromagnetic matter.(Figure 10) Therefore, it is not surprising that magnetic monopoles can be bound to this material. If the domain is isolated (and in its ground state) the passage of the monopole must conserve energy, because the monopole interacts with the $\vec{H}$ field. The fact that monopoles interact with $\vec{H}$ and not $\vec{B}$ is related on the microscopic level to the vanishing of the s wave interaction between monopoles and electrons. When a monopole approaches an unmagnetized ferromagnetic medium it will experience an attractive force caused by the induced magnetization or image magnetic charge, with a potential minimum at the domain boundry. Figure 11 shows the forces due to image charge on the monopole.

There have been several calculations of the binding energy, the earliest being those of Malkus and Goto. These calculations were made for macroscopic matter. Kittel and Maniku refined this calculation to include the ferromagnetic exchange interaction. Their estimate for the binding energy is ~ 50 ev, to a single domain which is not inconsistent with the classical calculation of Goto, which includes the full domain structure. There have been several calculations of the binding of monopoles and either electrons or nucleons. There is no clear consensus as to whether monopoles and electrons have bound state solutions although such solutions have been found for electrons with an extra magnetic moment. For monopole - nuclei systems it appears that an appreciable binding energy is expected. For example, the estimated binding energy of a (monopole - Al^{27}) system is 2 MeV[12].

For small velocity monopoles the velocity of the electrons in the atom are of comparable size. This should enhance the pickup by ions or monopoles. The pickup probability has been estimated in the following manner. Consider a monopole with low velocity ($\beta \approx 10^{-3}$) passing by an Al_{27} atom or nucleus, the center of mass energy of the monopole Al_{27} system is $\sim 10^{-2}$ MeV, whereas the estimated binding energy is ~2 MeV. Nuclei or electrons can be captured by the radiative mechanism, the $\sim 10^{-2}$ MeV center of mass energy is carried away by the bremsstrahlung of the accelerated nucleus or electron in the monopole field. C. Goebel has estimated the average energy radiated per collision as $\sim 10^{-5}$ MeV which leads to a monopole - Al_{27} capture probability of $\sim 10^{-5}$ and a capture cross section of 10^{-5} barns, thus the capture distance in the earth is ~250 Km. Monopoles with velocity $\beta > 10^{-5}$ are expected to pass through the earth if they remain as free monopoles. Once an Al_{27} atom or nucleus has been picked up, if the atom is stripped, the stopping probability in the traversed through the earth will increase. Thus it is possible that the flux of monopoles passing up through the earth is decreased relative to the flux at the surface of the earth. However, the Baksan monopole search was sensitive to monopoles coming up from below or down through the ~300 M overburden (the expected charge pickup probability in the over burden is [.3 Km/250 Km ~ 10^{-3}] and rapidly increases with increasing zenith angle).

The binding of monopoles to magnetic structures or to individual nuclei or atoms will have important consequences for the search for small concentrations of monopoles in matter.[43,44] We will return to this subject later in this report.

3.5 Pickup of Nuclei and Atoms

Occasionally a monopole passes close to or penetrates a nucleus. The potential energy of the monopole-nucleus system is[43,44] $U = -\vec{\mu}\cdot\vec{B} = 10^{-25}\mu/r^2$ MeV. Where $\vec{\mu}$ is the nuclear magnetic moment (in units of μ_M). Goebel has shown that any nucleus with a gyromagnetic ratio greater than 2 will be attracted by a monopole. The potential energy of the ground state is $V \simeq (Z-A\mu)\mu_N g/Ar^2$. For hydrogen (r = 1.4 F), V = -8 MeV. With the approximate substitution $Z \simeq A/2$, $r \simeq 14\, A^{1/3}F$, we obtain $V \simeq 2.5\ (1-2\mu)A(-2/3)$ MeV. For hydrogen, the kinetic energy of the ground state orbit will be considerable, so the binding energy will be ~1 MeV. For heavier nuclei (eg. Al, Na, Cl) the kinetic energy will be small, so the binding energy will be B ~ 2 MeV. The kinetic energy of a nucleus in the monopole frame is $T \simeq 1/2 A m_p C^2\beta^2 \sim 10^{-2}$ MeV. Since T<<B, once a nucleus was bound to a monopole it would not be disrupted as the bound system continued through the earth.

Goebel has estimated the cross-section for nuclear capture.[44,45] In order for a nucleus to be captured, it must undergo a momentum transfer either to the monopole or as a radiated photon. The interaction cross-section is

$$\sigma_{int} = \frac{\pi h^2}{2\beta^2 m_p^2 c^2}\frac{(A\mu - Z)}{A^2} = \frac{8.4 \times 10^{-29}}{\beta^2}\ cm^2. \qquad (10)$$

Goebel has calculated the probability P_γ that the nucleus emits a Bremsstrahlung photon of sufficient energy to allow capture. He obtains $P_\gamma = 4 \times 10^{-5}$. The mean free path for capture with $\beta_m = 5 \times 10^{-3}$ is $\lambda = (N\sigma_{int}P_\gamma)^{-1} = 1.2$ km.

According to this estimate significant fraction of incident monopoles entering a cave experiment from above (and all entering from below or horizontally) will have captured nuclei.

The large ionization energy loss for monopoles with trapped nuclei (along with the new calculations of Ahlen and Kinoshita)[10] increases the probability that monopoles stop in the earth, Jupiter or the Sun. Table 4 gives an approximate velocity at which monopoles stop in these objects. The large ionization loss also increases the detection probability. For example, Figure 5 shows the effect on scintillation detectors.

4. Possible Local Sources of Monopoles and Large Area Detection Techniques

4.1. Solar System Sources

The Parker bound on the flux of GUT monopoles applies to the case where monopoles are uniformly distributed throughout the galaxy, and their flux must be consistent with the survival of the known galactic magnetic field.[20,21] The terrestial flux of monopoles could, however, exceed the Parker bound by many orders of magnitude if there were a local concentration or source, which would then be subject only to the less restrictive bounds imposed by the survival of local magnetic fields. The number density of monopoles is bounded by[20]

$$n(cm^{-3}) < B/8\pi g v \tau \qquad (11)$$

where B is the magnetic field (gauss), g is the Dirac magnetic charge ($e/2\alpha$ in esu) v is the monopole velocity (cm/sec), and τ is the field regeneration time (sec).

The constraints implied by this relation had been worked out for solar system sources by Dimopoulos et al. [12] and Glashow[23], in an attempt to find an acceptable local reservoir of monopoles consistant with the flux implied by the Cabrera event,[24] if it were actually a monopole. They conclude that the known magnetic fields of the sun and the earth preclude these bodies from harboring a high enough concentration of monopoles to explain the Cabrera event, by many orders of magnitude. However, they point out that the high flux implied by the Cabrera event could be explained by a local source in the form of a diffuse cloud of monopoles, orbiting the sun much like meteors or meteoric dust. The density $n \sim 10^{-15}/cm^3$ is consistent with the survival of the solar-system magnetic field, and could be maintained by an influx of monopoles from either the sun or the galaxy. The monopole densities implied for the sun, the galaxy and the earth are all consistent with known magnetic fields.

Glashow[23] treats the case where the sun is the primary reservoir of monopoles. Kilogauss internal solar fields would be implied, and other stars would also concentrate monopoles. If monopoles were to catalyze nucleon decay[25,26] in the sun, a significant solar energy source could be implied. The increase in solar luminosity turns out to be acceptably small, but the effect on solar energetics and a possible terrestrial flux of high energy neutrinos could be detectable consequences of this model. While this steady-state situation seems to be consistent with all observations, it is not clear how the sun could have collected the required number of monopoles in the time since its birth without a violation of the Parker bound on the galactic monopole flux.

4.2 Sources Near the Earth

It is generally recognized that the trapping of very massive GUT monopoles in matter is likely to require rather delicate circumstances, owing to the large ratio of gravitational to magnetic force on a monopole. Except for trapping in ferromagnetic materials, very slow monopoles are not likely to stop on the earth's surface, but would fall into the earth's core.

Longo[19] has treated in detail the case of GUT monopoles trapped in matter, and has concluded that iron meteorites are one of the best places to search for monopoles. Unlike terrestrial iron deposits, many meteorite samples may not have been heated above the Curie temperature or oxidized since they were condensed from the solar nebula. They therefore could have collected monopoles over a very long time. Monopoles trapped in iron grains which are embedded in stony meteorites would be insulated from thermal effects during their fall to earth. Furthermore, iron grains of sufficiently small size ($\sim 10^{-3}$cm) would not permit trapped monopoles to gain enough energy to escape through the grain's surface by falling within the grain itself. The effects of meteorite impact on the earth's surface would vary widely, but would be minimized for monopoles which happend to fall in deep snow. A large sample of Antarctic meteorites exists. Longo points out that the monopole concentration limits obtained by Eberhard[28] from 2 kg of meteorites are therefore particularly relevant, and imply a concentration of less than 10^{-27} monopoles/nucleon. This is several orders of magnitude more restrictive than the Parker bound.

4.3 Detection Techniques: Size Limitations

Direct experimental limits on the abundance of GUT monopoles are presently rather poor, reflecting the short time which has elapsed since very large monopole masses were firmly predicted by grand unified theories.[30,32,33,51,52] Substantial improvements can be expected in the next few years as existing experiments continue to run and experiments now in preparation come into operation. The sizes of all types of detectors can in principal be expanded significantly beyond those presently in operation, although often at considerable cost. Table 3 summarizes the present and possible future sensitivities of the main detector techniques.

It is clear from Table 3 that a very ambitious program will be required to detect monopoles at levels much below the maximum flux allowed by the Parker bound; detectors even larger than those listed for the future are needed. Given the prejudice that monopoles may have velocities $\sim 10^{-4}c$, the scintillator technique seem quite promising, particularly if it can be pushed to lower ionization levels, as has been done on a small scale by Groom et al.[23] The infrared phosphor technique now being developed by Hagstrom[18,35] could possibly lead to a very large detector which is sensitive to velocities $\sim 10^{-4}c$, but the actual performance capabilities and cost are still unknown. It is also clear that the stable matter searches can be improved by many orders of magnitude[26], although monopoles could still elude detection if the correct materials are not chosen or if all monopoles have collected in inaccessible locations. On the other hand, if magnetic monopoles should turn out to be as common as the event observed by Cabrera would indicate, we should soon have a large sample of monopole events to study without having to build the large detectors suggested in Table 3.

Table 1. Astrophysical Limits on the Abundance of GUT Magnetic Monopoles. The references quoted typically give monopole abundance limits in terms of either flux F or number density n. The velocities v shown are used to translate between these two types of limits using the relation $F = nv/2\pi$, where it is meaningful to do so.

Reference	Monopole location	Measured quantity	Abundance Limits F ($cm^{-2}sr^{-1}s^{-1}$)	velocity	n (cm^{-3})
Longo[19]	uniform in universe	mass of universe	2×10^{-12}	$10^{-2}c$	4×10^{-20}
Turner[20]	galaxy	galactic B field	1×10^{-15}	$10^{-3}c$	2×10^{-22}
Glashow[21]	galaxy	galactic B field	5×10^{-18}	$10^{-3}c$	1×10^{-24}
Carrigan[22]	earth's core	heat from annihilation	--	--	1.5×10^{-3}
Dimopoulos[12]	earth	earth's B field	—	$10^{-5}c$	1×10^{-9}
Dimopoulos[12]	sun	sun's B field	—	$10^{-3}c$	1×10^{-7}
Dimopoulos[12,23]	solar system	Cabrera[24] event	6×10^{-10}	$10^{-3}c$	1×10^{-15}

Kolb[18]	neutron stars	x-rays from proton decay	$5x10^{-22}$	$10^{-3}c$	$2x10^{-29}$
Ellis[26]	flux at proton decay experiments	$\tau_p > 3x10^{30}yr$	$2x10^{-15}$	$10^{-3}c$	$4x10^{-22}$

Table 2. limits on the Flux of GUT magnetic Monopoles from Direct Measurements. The velocity ranges given are those quoted by the authors, and generally use quite different assumptions for the ionization at low velocities, $v \sim 10^{-3}c$. The number of monopoles per nucleon, n_M/n_N, is given for the stable matter searches.

Reference	Sensitive material	Ionization required (I_{min})	β range	Abundance Limits F ($cm^{-2} sr^{-1} s^{-1}$)	n_M/n_N
Ross[27]	super-conducting loop		trapped, 20 kg of moon rocks	—	$3x10^{-28}$
Eberhard[28]	super-conducting loop	--	trapped, 2 kg of meteorites	--	$3x10^{-27}$
Kinoshita[29]	CR-39	900	>0.02	$2x10^{-13}$	--
Baksan[30]	liquid scintillator	0.25	$5x10^{-3}$-0.1	$1x10^{-14}$	--
Bonarelli[31]	scintillator	25	$7x10^{-3}$-0.6	$2x10^{-12}$	--
Groom[32]	scintillator	0.12	$1x10^{-4}$-$3x10^{-2}$	--	
Ullman[33]	argon gas	2.5	$3x10^{-4}$-$1x10^{-3}$	$6x10^{-11}$	--
Soudan 1[34]	argon gas	0.5	$2x10^{-3}$-$2x10^{-2}$	$7x10^{-13}$	--
Cabrera[24]	super-conducting loop	--	--	$6x10^{-10}$	--

Table 3. Present and Future Monopole Detector Sensitivities. Present flux limits are often determined by the short operating periods so far accumulated; future limits assume 1 monopole in 3 years of operation. Flux limits can be compared with the Parker bound of $\sim 10^{-15} cm^{-2} sr^{-1} s^{-1}$.

Technique	Velocity Range (β)	Present Size ($m^2 sr$)	Present Flux limits ($cm^{-2} sr^{-1} s^{-1}$)	Future Size ($m^2 sr$)	Future Flux Limit ($cm^{-2} sr^{-1} s^{-1}$)
CR-39[29]	$>10^{-2}$	75	2×10^{-13}	1000	1×10^{-15}
Scintillator[30]	10^{-3}–10^{-2}	1800	1×10^{-14}	5000	2×10^{-16}
Silicon[18]	10^{-4}–10^{-2}	--	--	0.1	1×10^{-11}
Infrared Phosphor[18]	10^{-4}–10^{-2}	--	--	1000	1×10^{-15}
Superconducting coil and SQUID:					
In flight[24]	all β	0.013	6×10^{-10}	10	1×10^{-13}
Stable matter	--	~40 kg searched[19,20]	$\sim10^{-28}$ monopoles/ nucleon	10^9 kg Fe ore[19]	10^{-36} monopoles/ nucleon

5. Search for Monopoles Trapped in Very Old Material

To date the total amount of matter processed in a search for magnetic monopoles ≈100 kg. In order to carry out a sensitive experiment extends the limits appreciately, a method has been proposed in which $\sim 10^6$ tons of material or 10^9 more material than previous experiments is processed. The search for monopoles trapped in matter requires that very slow monopoles be detected ($\beta < 10^{-5}c$).

The direct detection of monopoles with low velocity ($v/c < 10^{-5}$) must be carried out by interaction with bulk electrical-magnetic systems - i.e. superconducting coils in which magnetic flux is trapped. We can attempt to estimate the possible numbers of trapped monopoles in 10^6 tons of iron ore by the following argument - 10^6 tons of ore spreadout corresponds to an area of 1 km x 1 km and a depth of ~1/2 meter. The material was exposed for 2×10^9 years - thus the integrated flux of monopoles through this area is related to the limits of the flux in cosmic rays. One half of the monopoles would pass through this area coming up from the earth. We estimate the capture probability from the ratio of the thickness of the material to that of the earth. These estimates indicate that less than 1 monopole should be trapped in a ton of iron ore if the Parker Bounds are correct. Of course, there are local sources of monopoles and a large fluxes, this estimate could be far to low.

Because the density of trapped monopoles in iron ore should be proportional to the amount of time that the ore has been below the Curie point, it is important to choose an ore from a body of the greatest possible geological age. Of the ore being mined now, there are 3 major types that have been around for a significant period. Fig. 12 shows a "history" of iron ores on earth.

Volcanic iron ore is simply iron ore brought to the surface from a depth approximately 15-20 kilometers be a volcano which speud it over the surrounding area. This type of ore is the youngest and is approximately 40-60 million years old. Not many deposits of this ore currently being mined in the continental U.S. though with any significant throughput, however.

Contact Metamorphic iron ore is formed when hot magna intrudes from below into a pocket if softer rock, particularly limestone, passing through it and leaving iron ore behind after it cools. This type is generally mined in Utah and is approximately 200-600 million years old.

Sedimentary iron ore is the oldest and most stable type and is formed in the following way: First a volcanic iron ore deposit is formed. This eventually is weathered with the iron carried to shallow seas or lagoons where it ends up as sediment though a series of chemical reactions. Eventually the sea floor is raised up and the iron is now in in the sedimentary rock. This type is found extensively in Wisconsin and Minnesota where it has spread in great sheets approximately 1.8-2.2 billions years old. It is also the type most likely to have trapped monopoles in it due to the dry period it has been around. It is also mined in large quantities which makes it ideal for a monopole search.

A prototype experiment to search for monopoles in old iron ore heated above the Curie temperature is being carried out by the Wisconsin group at Black River Falls, Wisconsin.[36] The initial detector is shown in Figure 9 and it consists of 4 superconducting coils and 3 SQUIDs. Future searches using $>10^7$ tons of iron ore might be carried out at large plants like the one shown in Figure 13.

6. Research and Development on Detection of Monopoles - Future Searches

There are already a number of monopole detectors in operation; some like the Baksan detector are very large. However, each detector has either a limited area or a limited velocity sensitivity range. In particular the velocity range of 10^{-3} - 10^{-5} suffers from an inadequate and relatively inexpensive detection technique. On the other hand, the recent calculations of dE/dx at low velocity for monopoles gives some confidence that detectors like the Baksan detector will function adequately for $\beta > 10^{-3}$.

Several ideas have been advanced for constructing "ionization" or "eddy current" detectors that may be sensitive in the 10^{-3}-10^{-5} velocity range. We will simply make a list of these ideas here. We feel that considerable research and development should be carried out on some (or all) of these techniques, given the extreme importance of the search for magnetic monopoles.

These techniques are:

1. Use of Infrared detector to detect the IR light from excited electrons.[35]
2. Use of Electron Drifting Detector (Si detectors, Liquid Argon Detectors).[33]
3. Use of Zeeman or Magnetic Pumping of Levels to detect slow monopoles.
4. Use of "superconducting rings" in organic materials.
5. Use of Eddy current - acoustical signals.
6. Use of magnetic structure - domain flipping effects.
7. Use of magnetic bubble techniques.
8. Use of normal coils with narrow band pass amplifers.

For the velocity range below 10^{-5} it seems superconducting coils will be the only sure technique. However, the use of domain flipping detectors might also be useful, if a technique to calibrate the detector could be developed.

Table 4

Monopoles In Sun and Planets

	R(cm)	M(g)	ρ(gm/cm^2)	$\beta^{dE/dx}_{stop}$	β_{escape}
Earth	6.4×10^8	$\sim10^{26}$	~2.7	$\sim4\times10^{-5}$	$\sim2\times10^{-5}$
	Saturn6×10^9	5.7×10^{39}	~2.5	$\sim3\times10^{-4}$	
Jupiter	7×10^9	1.9×10^{39}	3.3	$\sim3\times10^{-4}$	
Sun	7×10^{10}	2×10^{33}	160	$\simeq10^{-2}$	$\sim10^{-4}$
Galaxy	$\beta_{escape}\sim10^{-3}$				
Virgo Cluster	β_{escape}	$\sim3\times10^{-3}$			

References

1. P.A.M. Dirac, Pro. Roy. Soc. Lond., Soc A133, 60 (1931) and Phys. Rev. 74, 817 (1948).
2. G. ´t Hooft, Nucl. Phys. 879 276 (74), A. Polyakov, ZhETF Pis. Red. 20., 430 (1974). ((JETP Lett. 20. 194 (1974).)) J.C. Pati and A. Salam, Phy. Rev. Lett. 31, 661 (1973); H. Georgi and S.L. Glashow, Phys. Rev. Lett. 32, 438 (1974); H. Georgi, H.R. Quinn, S. Weinberg, Phys. Rev. Lett. 33, 451 (1974). P. Langacker, "Grand Unified Theories", 1981 Int. Symp. on Lepton and Photon Interactions. J.P. Preskill, Phys. Rev. Lett. 43, 1365 (1979). M.B. Einhorn, D.L. Stein, and D. Toussaint, Phys. Rev. D21, 3295 (1980). F.A. Bais and S. Rudaz, Nucl. Phys. B170, 507 (1980). A.H. Guth, Phys. Rev. D23, 347 (1981); A.H. Guth and E. Weinberg, Phys. Rev. D23, 876 (1981). P. Langacker and S.-Y. Pi, Phys. Rev. Lett. 45, 1 (1980). M. Daniel, G. Lazarides, and Q. Shafi, Phys. Lett. 91B, 72 (1980). F.A. Bais, Phys. Lett. 98B, 437 (1981) and F.A. Bais and P. Langacker, TH, 3142-CERN. S. Bludman, 1981 Renc. de Moriond, UPR-0175T.
3. G. Lazarides, Q. Shafi, and T.F. Walsh, Phys. Lett. 100B, 21 (1981). E.N. Parker, Cosmic Magnetic Fields, Oxford (1979). M.J. Longo, "Massive Magnetic Monopoles: Indirect and Direct Limits on their Number Density and Flux", UM-HE-81-33 (1981). E.N. Parker, Ap. J. ,160, 383, (1970). S.A. Bludman and M.A. Ruderman, Phys. Rev. Lett. 36, 840 (1976).
4. For magnetic monopole review see, P. Goddard and D. Olive, Rep. Prog. Phys. 41, 91 (1978); C.N. Yang in Proceedings of the 19th International Conference on High Energy Physics, Tokyo, 1978 edited by S. Homma, M. Kawaguchi, and H. Miazawa; W. Marciano and H. Pagels, Phys. Rep. 36C, 137 (1978); A. Jaffe and C. Taubes, Vortices and Monopoles:, Structure of Static Gauge Theories (Birkhauser, Boston 1980); Monopoles in Quantum Field Theory: Proceedings of the Monopole Meeting, Trieste, edited by N. Craigie, P. Goddard and W. Nahm, (singapore, World Scientific Publishing CO.,1982).
5. G. ´t Hooft, Nucl. Phys. B79, 276 (1974).
6. A. Polyakov, JETP Letters 20, 194 (1974).
7. H. Georgi and S. Glashow, Phys. Rev. Lett. 32, 438 (1974).
8. Y. Zeldoirch and M. Khlopov, Phys. Lett. B79, 239 (1978); J. Preskill, Phys. Rev. Lett. 43, 1365 (1979).
9. A. Guth and S.-H. Tye, Phys. Rev. Lett. 44, 631 (1980); A. Guth and E. Weinberg, Phys. Rev. D23, 876 (1981); A. Linde, JETP Lett. 32, 516 (1981).
10. S.P. Ahlen, Phys. Rev. D17, 229 (1978); S.P. Ahlen and K. Kinoshita, Berkeley preprint (1982); S. Geer and W. Scott, CERN preprint
11. B. Cabrera, Phys. Rev. Lett. 48, 1146 (1982).
12. For a contrary view, see S. Dimopoulos et al., "Magnetic Monopoles: A Local Source?" Harvard U. preprint HUTP-82/A016 (1982) (unpublished).
13. E. Parker, Ap. J. 163, 225 (1971), ibid., 166, 295 (1971); N. Turner, E. Parker and T. Bogden, Enrico Fermi Inst. preprint (1982).
14. C. Dokos and T. Tomaras, Phys. Rev. D21, 2940 (1980); D. Scott, Nucl. Phys. B171, 95 (1980).
15. J. Schwinger, Phys. Rev. 144, 1087 (1966).
16. U. Rubakov. JETP Letters 33, 644 (1981).
17. C. Callan, Princeton U. preprint (1982).
18. E. Kolb, S. Colgate and J. Harvey, "Monopole Catalysis of Nucleon Decay in Neutron Stars, LANL preprint (1982)(unpublished).
19. M.J. Longo, Phys. Rev. D25, 2399 (1982).
20. M.S. Turner, E.N. Parker, and T.J. Bogdan, "Magnetic Monopoles and the Survival of Galactic Magnetic Fields", Enrico Fermi Institute Preprint No. 82-18, 1982 (unpublished); E.N. Parker, Astrophys. J. 160, 383 (1970).
21. S.L. Glashow, "Physics in underground laboratories", proceedings of the workshop on Physics and Astrophysics with a Mulotikiloton Modular Underground Track Detector, edited by G. Ciapetti, F. Massa, and S. Stipich, published by Servizio Documentazione dei Laboratori nazionali di Frascati, 1982, p. 1.
22. R.A. Carrigan, Jr., Nature 288., 348 (1980).
23. S.L. Glashow, "Magnetic Monopoles About Us", Harvard Preprint No. HUTP-82/A)18; to be published in the proceedings of the Third Workshop on Grand Unification, Chapel Hill, North Carolina, 1982.
24. B. Cabrera, Phys.Rev. Lett. 48, 1378 (1982).
25. V.A. Rubakov, Zh. Eksp. Teor. Fiz. 33, 658 (1981); JETP Letters 33, 644 (1981).
26. J. Ellis , D.V. Nanopoulos, and K.A. Olive, "Baryon Number Violation Catalyzed by Grand Unified Monopoles", CERN preprint Ref.TH.3323-CERN, 1982 (unpublished).
27. R.R. Ross et al., Phys. Rev. D8, 698 (1973).
28. P.H. Eberhard et al., Phys. Rev. D4, 3260 (1971).
29. K. Kinoshita and P.B. Price, Phys. Rev. D24, 1707 (1981).
30. A. Chudakov, private communications to D. Cline and P. McIntyre.

31. R. Bonarelli et al., Phys. Lett. 112B, 100 (1982).
32. D.E. Groom, E.C. Loh, and D.M. Loh and D.M. Ritson, "A Search for a Slow-moving Flux of Massive Magnetic Monopoles", Univ. of Utah preprint No. UUHEP 82/2, contributed paper to the XXI International Conference on High Energy Physics, Paris, 1982.
33. J.D. Ullman, Phys. Rev. lett. 47, 289 (1981).
34. D.S. Ayres, "Planning for the Next Generation of Proton Decay Experiments in the United States", Argonne National Laboratory preprint No. ANL-HEP-CP-82-17; to be published in the preceedings of the Third Workshop on Grand Unification, Chapel Hill, North Carolina, 1982.
35. R. Hagstrom, "Comments on GUT Monopole Energy Loss and Ionization", to be published in the proceedings of the 1982 Summer Workshop on Proton Decay Experiments, Argonne National Laboratory report No. ANL-HEP-PR-81-24, 1982.
36. D. Cline et al., "A New Experimental Technique to Search for Relic Magnetic Monopoles", Univ. of Wisconsin proposal to the U.S. Department of Energy, 1982; D. Cline, "The Search for Magnetic Monopoles", presented at the Meeting on Experimental Tests of Unified Theories, Venice, March 1982.
37. The various limits and references are summarized in the proceedings of the Monopole Seminar, University of Wisconsin, 1981 (D. Cline) and in a report given at the Venice Meeting on Tests of Unified Theories. See also G. Giacomelli, Review of the Experimental Status (Past and Future) of Monopole Searches - Proceedings of the Conference on Monopoles in Quantum Field Theory - Trieste Dec. 1981, and S. Glashow, talk given to the GUD Meeting, Oct. 1981, Rome.
38. A. Chudakov, private communication and report at the ICOBAN Conference, Bombay, 1982. Also report given at Quarks 82, Sukumi, USSR (May 1982).
39. K. Schatten, Search for Magnetic Monopoles in the Moon, Phys. Rev. D., 1, 2245 (1970).
40. E. Fermi and E. Teller, Phys. Rev. 72, 399 (1947).
41. There is a great deal of confusion concerning the energy loss of very low velocity monopoles. Different calculations have provided predictions that the energy loss falls like β, β^2, β^3 and on calculation (McIntyre and Webb) indicates a constant energy loss with velocity.
42. D. Ullman, Phys. rev. Lett. 47, 289 (1981). S.P. Ahlen, Phys. Rev. D17, 229, (1978). S. Geer and W.G. Scott, "Calculation of the Energy Loss for Slow Monopoles in Atomic Hydrogen", CERN pp 69 (1981). P. McIntyre and B. Webb (private communications). K. Hagaski, dE/dx for Slow Monopoles, Kinki University, Hagaski-Osake, Japan preprint; S.P. Ahlen and K. Kinoshita, Calculation of the Stopping Power of Very Low Velocity Magnetic Monopoles, University California, Berkeley preprint.
43. The papers on electron-monopole bound states are: Y. Kazama and C.N. Yang, Phys. Rev. D15, 2300 (1977), C.N. Yang Bound States for the e-g System, Proceedings of the Conference on Monopoles in Quantum Field Theory, Trieste, Dec. 1981. C. Goebel, (private communication).
44. Papers on monopole-nuclei bound states are: W.V.R. Malkus, Phys. Rev. 83, 899 (1951). C. Calucci, Capture of Nucleons by a Monopole Lettere al Neovo Cimento, 32, 201 (1981), C. Goebel, Interaction of Monopoles with Atoms, Electrons and Nuclei, in Proceedings of the Monopole Seminars, Madison (1981) (D. Cline editor), C. Goebel and T. Kirkman, (private communication).
45. C. Goebel and Kirkman estimate that the monopole pickup distance for Al_{27}. in the earth is ~250 Km. (Proceedings of Monopoles Seminar, Madison, 1981).
46. J. Lindhard, Mat. Figs. Medd. Dan Vid. Selsk. 28, (1954); J. Lindhard and M. Scharff, Phys. Rev. 124 (1961); J. Lindhard, M. Scharff and H. Schiott, Mat. Fys. Medd. Dan. Vid. Selsk, 33 (1963); J. Lindhard, Mat. Fys. Medd. Dan. Vid. Selsk. 34 (1965).
47. W.-K. Chu, Methods of Experimental Phys., 17, 25 (1980).
48. J.F. Janni, Atomic Data and Nuclear Data Tables, 27 (1982).
49. Y. Kazama, C.N. Yang and A.S. Goldhaber, Phys. Rev. D15, 2287 (1977).
50. D.M. Ritson, SLAC-PUB-2950 (1982).
51. J. Sokolowski and L. Solac, "A Search for Lightly-Ionizing Slow Magnetic Monopoles", Univ. of Michigan preprint, June 1982.
52. E.A. Peterson, in proceedings of the 1982 Summer Workshop on Proton Decay Experiments, Argonne National Laboratories report ANL-HEP-PR-82-24, June 1982 (unpublished).
53. C. Rubbia, private communication.

Figure Captions

Fig. 1 The Evolution of the Universe - Radius vs time and mean energy.

Fig. 2 Limits on the Cosmic Monopole flux and Different Velocities.

Fig. 3 Revised Parker Bounds fpor the Flux of Cosmic Monopoles.

Fig. 4 Calculation of the Stopping Power of Slow Monopoles (Ahlen and Kinoshita).

Fig. 5 Estimates of Scintillation Light Yield for Slow Monopoles (Ahlen and Taric).

Fig. 6 Fig. 6a Very low energy stopping power for protons.

Fig. 6b,c Estimated Ionization Loss for Slow Monopoles by Ritson.

Fig. 7 Baksan Scintillation Detectot - 1800 m^2sr for $\beta > 10^{-3}$ Monopole Search.

Fig. 8 Graph from Cabrera paper on Possbile Monopole Event

Fig. 9 Wisconsin Monopole Detector

Fig. 10 Magnetic Field near a Monopole.

Fig. 11 Forces due to Image Charge near a Magnetic Monopole.

Fig. 12 History of Iron Ores in Earth

Fig. 13 Iron Ore Processing Plant where $>10^7$ Tons of Ore is Processed Per Year.

Figure 2

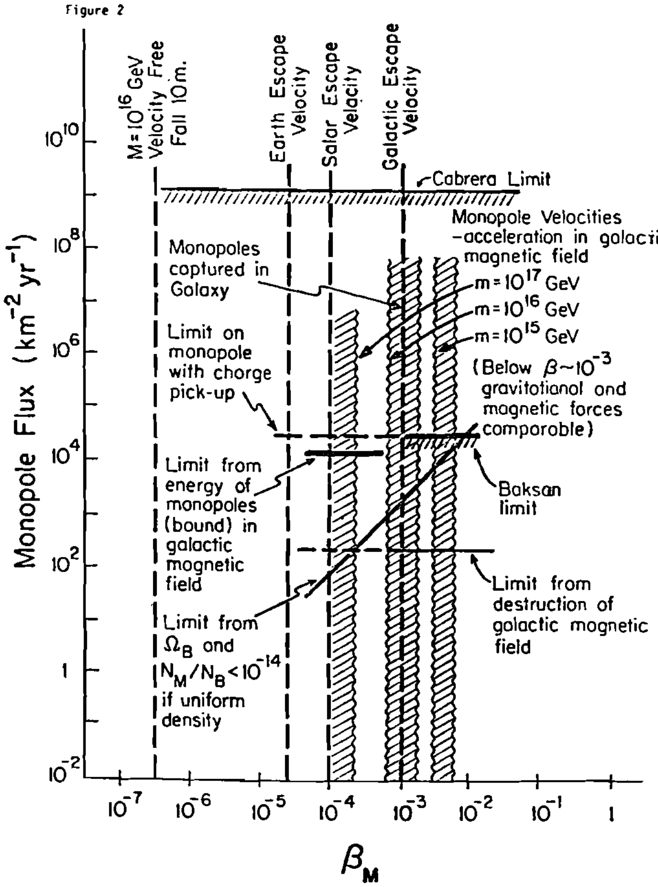


Figure 1

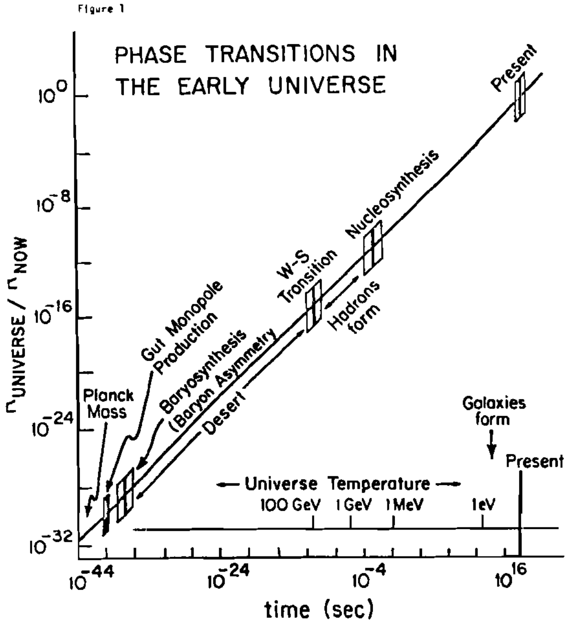
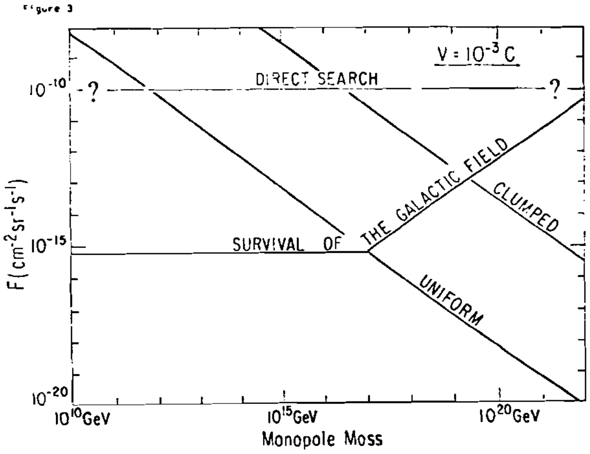


Figure 3



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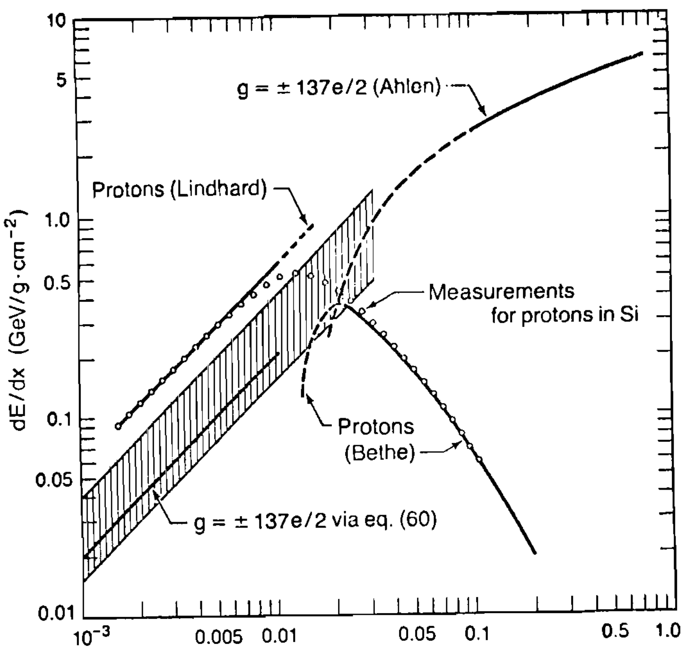

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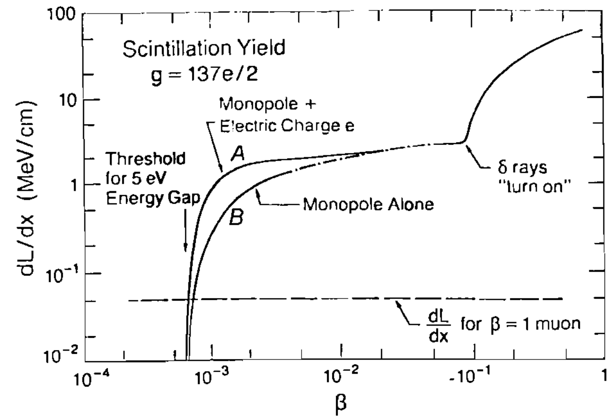


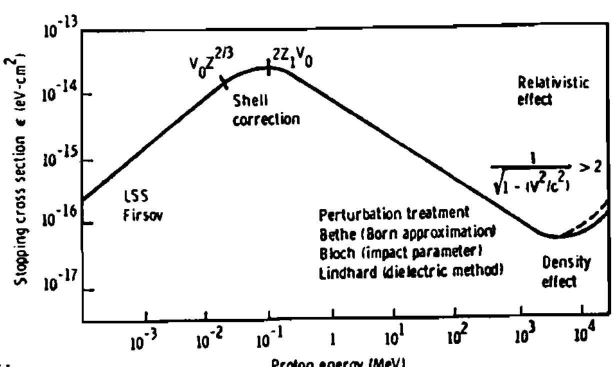


Figure 6 a Stopping cross section of protons in silicon. The general shape is described by various theories for various energy regions.

Figure 6 b

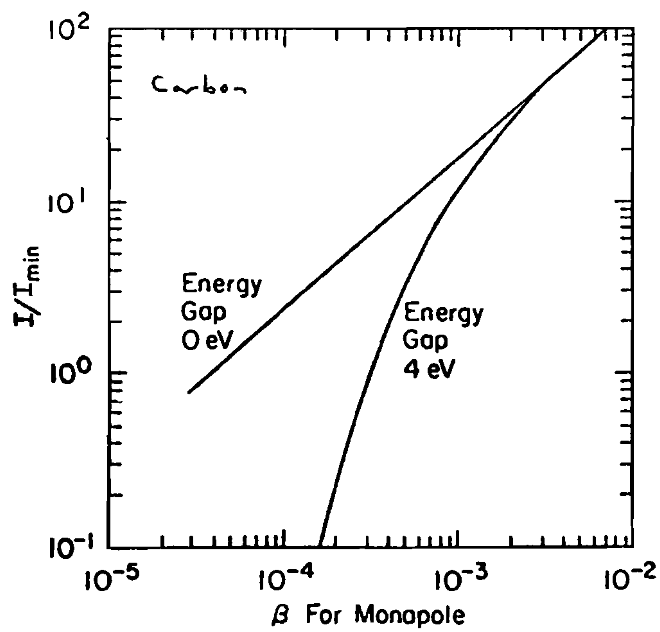
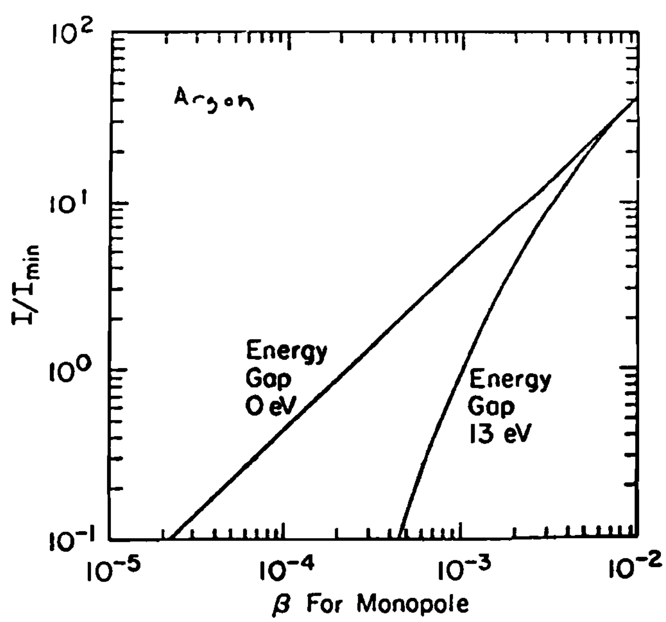


Figure 6 c



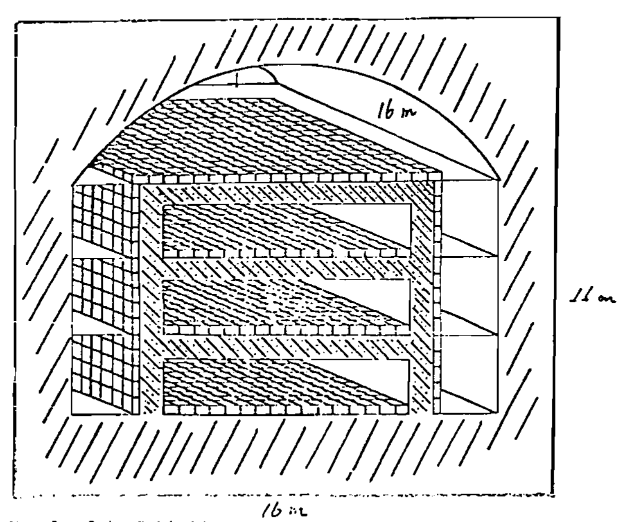


Figure 7 Baksan Neutrino Laboratory

Figure 8

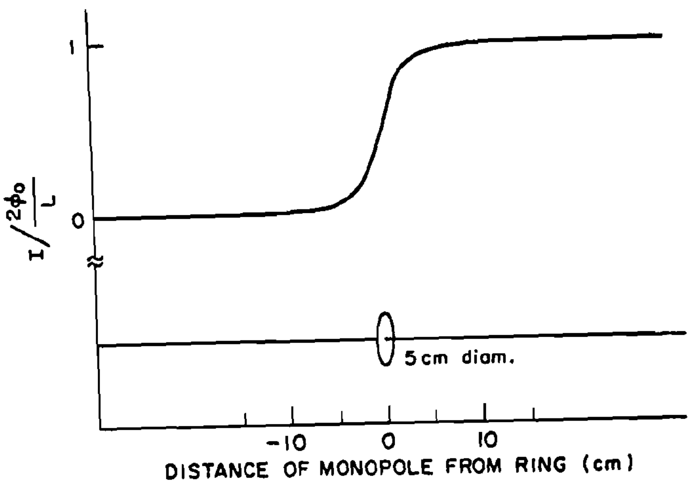


Figure 10

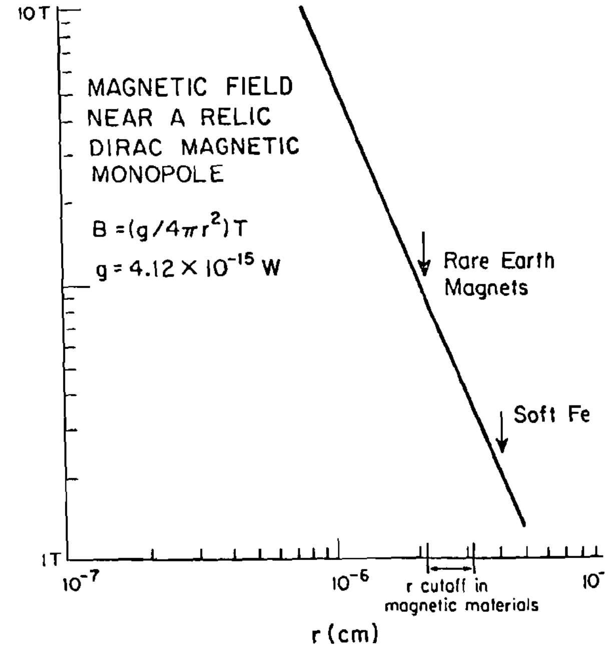


Figure 9

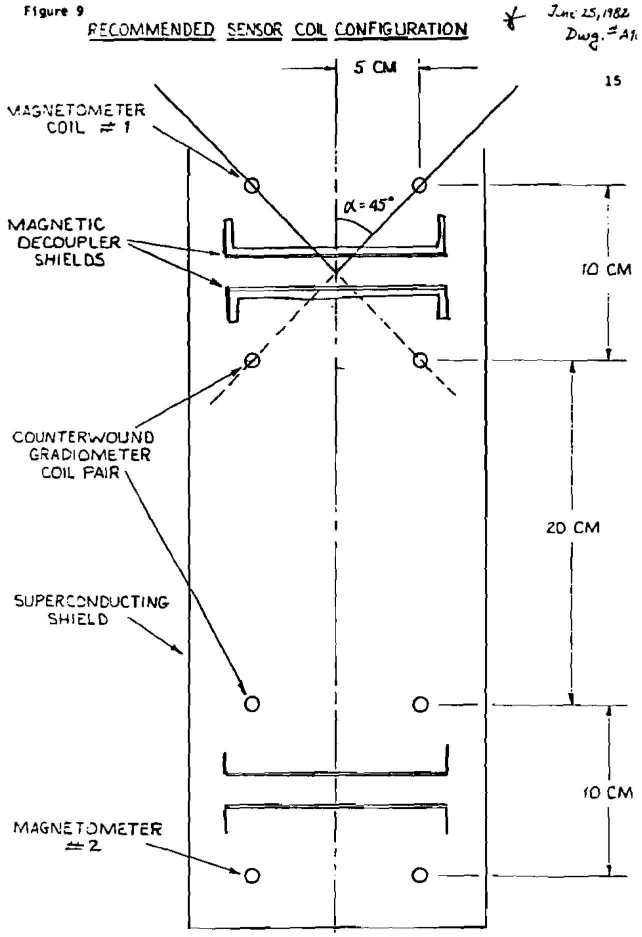


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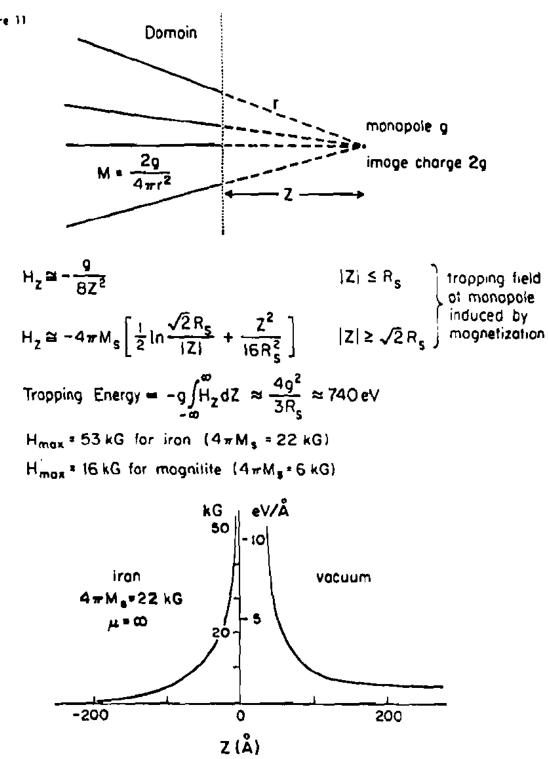
Figure 11



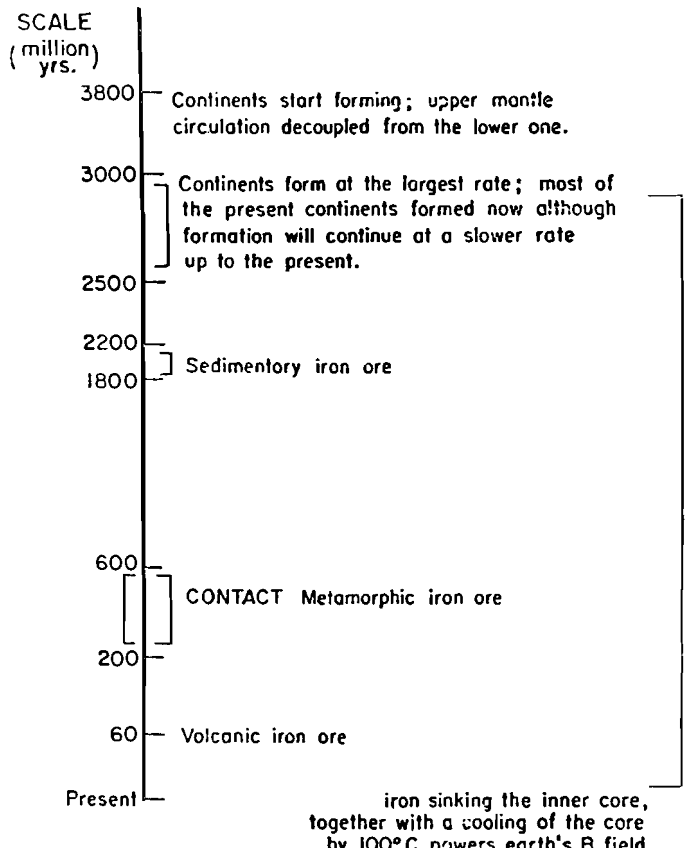
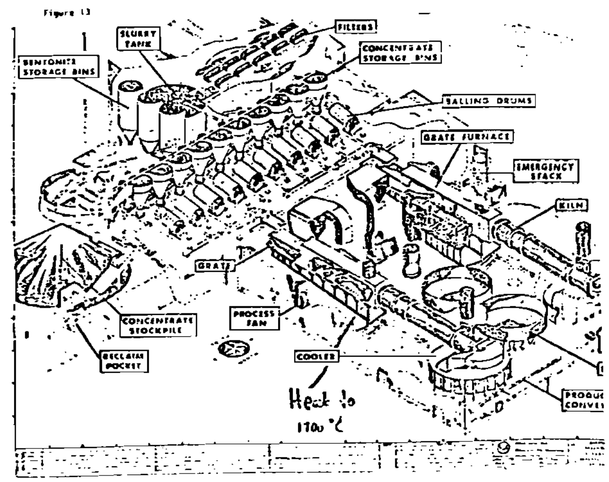

SCALE
(million yrs.)
3800
Continents start forming; upper mantle circulation decoupled from the lower one.
3000
Continents form at the largest rate; most of the present continents formed now although formation will continue at a slower rate up to the present.
2500
2200
Sedimentory iron ore
1800
600
CONTACT Metamorphic iron ore
200
60
Volcanic iron ore
Present
iron sinking the inner core, together with a cooling of the core by 100°C powers earth's B field

Figure 12


FILTERS
BALLING DRUMS
GRATE FURNACE
EMERGENCY STACK
KILN
PROCESS FAN
COOLER