Search for Magnetic Monopoles in Polar Volcanic Rocks

K. Bendtz and D. Milstead
Fysikum, Stockholm University, SE 106 91 Stockholm, Sweden

H.-P. Hächler and A. M. Hirt
Department of Earth Sciences, Swiss Federal Institute of Technology, 8092 Zurich, Switzerland

P. Mermod*
Département de Physique Nucléaire et Corpusculaire, University of Geneva, 1211 Geneva, Switzerland

P. Michael
Department of Geosciences, University of Tulsa, Tulsa, Oklahoma 74104, USA

T. Sloan
Department of Physics, Lancaster University, LA1 4YW Lancaster, United Kingdom

C. Tegner
Department of Geoscience, Aarhus University, 8000 Aarhus, Denmark

S. B. Thorarinsson
Nordic Volcanological Center, Institute of Earth Sciences, University of Iceland, 101 Reykjavik, Iceland

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For a broad range of values of magnetic monopole mass and charge, the abundance of monopoles trapped inside Earth would be expected to be enhanced in the mantle beneath the geomagnetic poles. A search for magnetic monopoles was conducted using the signature of an induced persistent current following the passage of igneous rock samples through a SQUID-based magnetometer. A total of 24.6 kg of rocks from various selected sites, among which 23.4 kg are mantle-derived rocks from the Arctic and Antarctic areas, was analyzed. No monopoles were found, and a 90% confidence level upper limit of $9.8 \times 10^{-5}/\mathrm{g}$ is set on the monopole density in the search samples.

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The existence of magnetic monopoles was postulated in 1931 by Dirac as a means to explain electric charge quantization [1,2]. The Dirac quantization argument predicts that the fundamental magnetic charge $q_m = gec$ (in this definition, q_m is in SI units and g is a dimensionless quantity) is a multiple of the Dirac charge $g = Ng_D$, with $g_D = 68.5$ and N an integer number. Magnetic monopoles are also fundamental ingredients in grand-unification theories [3]. Although grand-unification monopoles would typically have masses of the order of the unification scale ($m \sim 10^{16}$ GeV), there are generally no tight theoretical constraints on the mass of a monopole.

Calculations within nonrelativistic quantum theory indicate that monopoles would bind to non-zero-spin nuclei through magnetic moment coupling, with binding energies of the order of several hundred keV when assuming a hard core [4]. Such binding is assumed as a working hypothesis in the present search. If isolated monopoles exist in nature, they are stable by virtue of magnetic charge conservation and they either reside inside astronomical bodies or move freely through open space to form a galactic halo. Throughout this Letter, ‘‘stellar’’ denotes monopoles already trapped in stardust before the formation of the Solar System and ‘‘cosmic’’ denotes free monopoles reaching the Solar System at a later time.

Signatures of direct monopole pair production have been explored at past high-energy particle colliders including the LEP, HERA, and Tevatron [5–10] and are being investigated with the Large Hadron Collider [11,12]. However, monopoles with masses above 7 TeV cannot be produced within the current collider programs. In this work, which probes monopoles in the mass range between the weak scale and the grand-unification scale, it is assumed that monopoles may exist as relics produced out of thermal equilibrium in the very early Universe. Models of cosmological inflation allow relic monopoles to be diluted down to non-catastrophic abundances [13]. However, the various inflationary scenarios which have been proposed can make very different monopole abundance predictions [14]. Other unknowns are the monopole-antimonopole annihilation cross section and the detailed mechanisms by which monopoles may have bound to matter during primordial nucleosynthesis. Even though there are presently no adequate models that describe to which extent relic monopoles would have accumulated inside astronomical bodies or be present in cosmic rays, abundances and fluxes can be constrained by experiments. Monopoles in flight have been sought with array detectors. These set tight constraints on the flux of cosmic monopoles incident on Earth [15–28] (only the most significant results are given here; see [29] for a complete list). Trapped monopoles have previously been sought in hundreds of kilograms of samples from Earth's crust [30–35], in rocks from the Moon's surface [36,37], and in meteorites [30,35]. This work presents the first search for monopoles in terrestrial igneous rocks at high latitudes.

Large planetary bodies such as Earth were molten during their formation, and this has lead to large-scale chemical differentiation. During this early phase, stellar monopoles, if present, will likely have sunk to the planet's core [38]. Stellar monopoles should therefore be depleted in planetary crusts, while the deep interiors of planets and stars, as well as the insides of some meteoroids, asteroids, and comets, would be the only places likely to contain them in non-negligible amounts.

Monopoles inside astronomical bodies of low viscosity possessing stable dipole magnetic fields would move to positions along the magnetic axis where the magnetic force $F_m = q_m B$ (B is the vertical component of the magnetic field) and gravitational force $F_g = ma$ (a is the gravitational acceleration) are in equilibrium:

$$m = \frac{g_D ecB}{a}\frac{g}{g_D} = A\frac{g}{g_D}. \qquad (1)$$

Although the early configuration of Earth's internal magnetic field is poorly known, paleomagnetic data suggest that Earth possessed a dipole field since at least ~3.5 billion years [39–41]. The configuration of the field close to Earth's core may be more complex, but the simple assumption of a dipole field over geologic time is reasonable. Carrigan estimated that monopoles with $g = g_D$ and $m = 10^{16}$ GeV would accumulate near Earth's inner core and developed a model of how monopole annihilation during geomagnetic reversals would contribute to the planet's internal heat, thus limiting the grand-unification-mass monopole density inside Earth to less than $\sim 10^{-4}/\mathrm{g}$ [42]. On the other hand, a lighter mass or higher magnetic charge will raise the equilibrium depth. We consider monopoles attached to nuclei with an equilibrium position above the core-mantle boundary. Down to a depth of 2900 km, Earth's mantle plays the role of an insulator between the molten outer core and the crust and has the properties of a plastic solid. Although mantle dynamics are complex and various competing geodynamical models exist, it can generally be assumed that the mantle slowly convects as a whole, with a full cycle taking approximately 400–500 million years [43]. Monopoles caught in the solid mantle would be unable to move freely. Instead, monopoles of both polarities would be transported up and down along with mantle convection, regardless of the field direction. Upon reaching the core-mantle boundary, they would sink through the liquid core due to the high mass before being attracted in the general direction of the polar regions due to the magnetic charge. Over geologic time, monopoles would migrate toward the magnetic axis. At Earth's pole, $a = 9.8\ \mathrm{m \cdot s^{-2}}$ and $B = 6.5 \times 10^{-5}$ T, in which case Eq. (1) yields $A_{\mathrm{surface}} = 1.2 \times 10^{13}$ GeV (presently, GeV is a unit of mass). A monopole carrying a single Dirac charge ($g = g_D$) and a mass of 10^{13} GeV or lower would therefore be expected to be found beneath Earth's polar crust and in melts below polar regions. A monopole carrying a multiple of the Dirac charge is allowed to possess a proportionally higher mass. This mass bound is conservative because monopoles with equilibrium anywhere inside the mantle may still reach the surface through mantle convection (the core-mantle boundary corresponds to $A_{\mathrm{boundary}} = 4 \times 10^{14}$ GeV). In a naive model, one may assume that monopoles would be distributed randomly throughout the whole mantle depth up to a distance from the magnetic axis equal to the core radius of 3400 km (this corresponds to latitudes $>57°$) and absent everywhere else. This results in a concentration of monopoles 6 times higher in polar mantle-derived rocks than averaged over Earth's mass.

The samples used in this search were restricted to mantle-derived igneous rocks with negligible levels of crustal contamination, emplaced at high ($> 63°$) latitudes. Basaltic rocks from hot spots—volcanic regions under which the mantle is thought to be locally hotter, causing an ascending mantle plume—are particularly attractive, as they are likely to include material from deep inside the mantle. Iceland and Hawaii are among the best known examples of hot spots for which there is evidence that the erupted material comes from more than 600 km depth and possibly as deep as the core-mantle boundary [44,45]. Other active hot spot sites at high latitudes, but for which the role of mantle plumes is debated [46], include Jan Mayen Island (Arctic Ocean) [47] and Ross Island (Southern Victoria Land, Antarctica) [48]. Large igneous provinces (LIPs) are also of interest for this work. These massive magmatic provinces are dominated by extensive flood basalt lavas with areal extents of $>100\,000\ \mathrm{km}^2$ and igneous volumes of $>100\,000\ \mathrm{km}^3$, most of which ($>75\%$) was expelled during relatively short periods (~ 1–5 million years) [49]. Furthermore, many LIPs have been associated with mantle plume activity and continental breakup [50]. The Kap Washington Group volcanic sequence (North Greenland) and the Skaergaard intrusion (East Greenland) were considered for this search as parts of the High Arctic and North Atlantic LIPs, respectively [51,52]. Midocean ridges, or rift volcanic zones where tectonic plates slowly move away from each other, are also of interest. Lava flows from Gakkel Ridge (Arctic Ocean) [53,54] provide attractive samples at a very high latitude (84° N). Finally, some rock samples were selected on the basis that chemical analysis reveals hints of deep mantle origins. Some basaltic lavas from Coleman Nunatak (Marie Byrd Land, Antarctica) contain particularly high $^{206}\mathrm{Pb}/^{204}\mathrm{Pb}$ ratios (denoted as high μ, or HIMU), which indicates a low extent of melting and a relatively deep origin [55]. In addition, some of the lavas carry nodules of lherzolite, which have been carried up from the mantle source rocks without melting. Control samples, which should not contain stellar monopoles because they fail one of the search criteria, were also included: crust-derived lavas from a subduction zone (Antarctic Peninsula) and samples from a hot spot or midocean ridge at low latitude (Hawaii, Mid-Atlantic Ridge, and East Pacific Rise). The samples were shaped either as cylinders of 2.5 cm diameter and about 2.5 cm length or crushed into fragments, which were placed into plastic cuboid boxes 2.3 cm on one side. The analyzed samples are listed in Table I and amount to a total of 23.4 kg of search samples and 1.2 kg of control samples.

Samples were measured with a 2G Enterprises, Model 755R, three-axis dc SQUID rock magnetometer housed in a shielded room at the Laboratory of Natural Magnetism, ETH Zurich. For magnetic dipoles, the current reverts to zero on complete passage through the magnetometer superconducting coils. However, a monopole would leave the signature of a persistent current. This technique allows us to directly measure the magnetic charge contained inside a sample without the need to extract monopoles and with no mass dependence. The current measurements were performed in steps, including measurements where the sample is inside the sensing coils as well as 50 cm away from the sensing coils before and after the pass. Occasional passes with an empty sample holder were made for background subtraction. The persistent current is defined as the measured value after a pass minus the value before a pass (subtracting the same quantity for the empty holder), normalized such as to give the strength of the magnetic pole contained in the sample in units of g_D. As described in detail in [59], the calibration was performed using the convolution method, which consists of profiling the magnetometer response as a function of distance for a sample with well-known magnetization and inferring the response for a monopole. As a calibration cross-check, the response to a magnetic pole was tested by introducing one extremity of a thin solenoid of 25 cm length with applied currents corresponding to values of magnetic charge of $0.124g_D$, $1.24g_D$, $12.4g_D$, and $124g_D$. The two methods yield consistent results within a normalization uncertainty of 10%.

Samples with a total magnetization $\geq 1.5 \times 10^5 g_D$ (or magnetic dipole moment $\geq 4.4 \times 10^{-5}\ \mathrm{A \cdot m^2}$) were found to sometimes cause the flux-locked loop of the SQUID to be lost and recovered at a different quantum level. This leaves a signal similar to what is expected from a monopole. Weaker moments generally did not show this effect. Precautions were therefore taken so that all samples would have magnetization levels below $1.5 \times 10^5 g_D$. Crushing the sample material into a gravel- or sand-sized powder randomizes the magnetic moments from the constituent ferromagnetic minerals, which reduces the dipole signal. This method was frequently used in this study. Alternatively, the magnetization can be reduced by more

TABLE I. Characteristics of the rock samples used in this search. If not otherwise specified, they were emplaced during the Cenozoic era. The control samples are indicated with (c). The latitude corresponds to the location at the time of emplacement.

Site	Latitude	Tectonic setting	Rock type	Samples	Mass (kg)
Iceland [56]	64° N	Hot spot, midocean ridge	Basalt	144	5.916
			Gabbro	26	1.404
Jan Mayen Island [47]	71° N	Hot spot	Alkali basalt	6	0.139
Hawaii (c)	21° N	Hot spot	Tholeiitic basalt	17	0.610
North Greenland [57]	72° N	LIP, 71–61 million years old	Alkali basalt, trachyte, trachyandesite, rhyolite	73	1.779
East Greenland [58]	68° N	LIP, intrusion	Gabbro	39	1.830
Gakkel Ridge	84° N	Midocean ridge	Tholeiitic basalt	26	0.707
Mid-Atlantic Ridge (c)	33° S	Midocean ridge	Tholeiitic basalt	8	0.207
East Pacific Rise (c)	28° S	Midocean ridge	Tholeiitic basalt	7	0.241
Southern Victoria Land	77° S	Hot spot	Basalt, basanite	233	8.163
Northern Victoria Land	72° S	Intraplate volcanism	Basalt, trachyte	12	0.335
Marie Byrd Land [55]	76° S	Intraplate volcanism	Alkali basalt (HIMU)	50	2.184
			Lherzolite	3	0.148
			Basalt, trachyte	17	0.440
Ellsworth Land	74° S	Intraplate volcanism	Basalt	11	0.300
Horlick Mountains	87° S	Intraplate volcanism	Basalt	1	0.021
Antarctic Peninsula (c)	63° S	Subduction zone	Basalt	5	0.146
Total search				641	23.366
Total control (c)				37	1.204

than 1 order of magnitude by exposing the sample to an alternating field. There is no risk of dislodging a trapped monopole if a binding energy of 100 keV or more is assumed. Demagnetization was carried out only on 10% of the Antarctic samples probed in this study.

Measurements of persistent currents after the first passage through the magnetometer are shown for all samples in Fig. 1 (top). In the range from $-0.1g_D$ to $0.1g_D$, the distribution is Gaussian, with a mean value of $-0.002 \pm 0.001g_D$ and a standard deviation of $0.026 \pm 0.001g_D$. Non-Gaussian tails slightly extend the distribution beyond this range. Five candidates out of 678 samples yield absolute values which deviate from zero by more than $0.25g_D$. The two first of these candidates yield the largest values ($0.8g_D$ and $1.6g_D$) and also have total magnetizations in excess of $10^5 g_D$, close to the $1.5 \times 10^5 g_D$ limit beyond which measurements are known to be unreliable. Additional measurements of the five candidates using various orientations of the samples are shown in Fig. 1 (bottom). These multiple measurements confirm the zero magnetic charge hypothesis. It is possible to get a rough estimate of the probability that a random sample containing a genuine monopole with $|g| = g_D$ would yield a persistent current close enough to zero to remain unnoticed. The probability to mismeasure the current by an absolute value which deviates from g_D by less than $0.25g_D$ is about 0.3% (out of 678 samples, only the first candidate discussed above satisfies this condition, but some of the other candidates are close enough that we conservatively assume two). The probability to mismeasure the current in the direction where it would cancel out the current induced by a hypothetical monopole (whose charge can be positive or negative) is 1/2. Thus, we obtain that $0.3\%/2 = 0.15\%$ of the signals with $|g| = g_D$ would escape detection, less if $|g| > g_D$. It is concluded that no monopoles with magnetic charge $|g| \geq g_D$ were present in the samples.

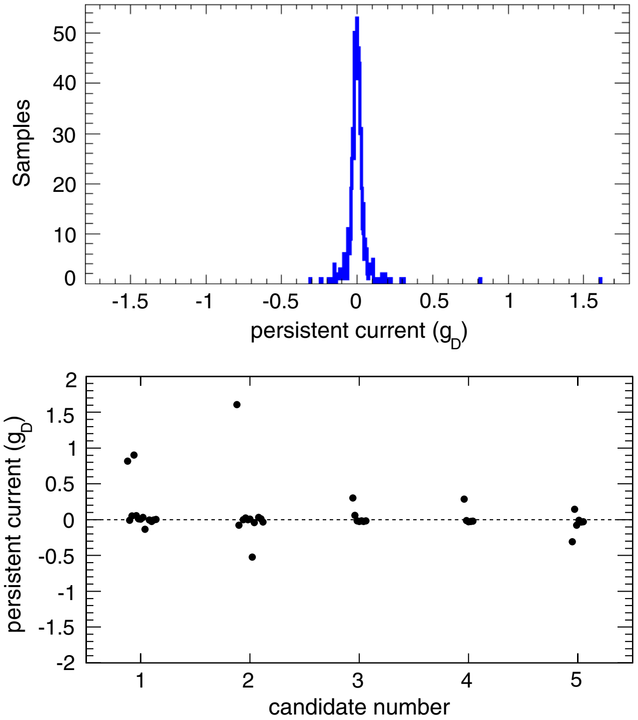

FIG. 1 (color online). Top: Persistent current after the first passage through the magnetometer for all samples. Bottom: Results of repeated measurements of candidate samples with absolute measured values in excess of $0.25g_D$.

The most extensive meteorite search to date—the only other direct search with a non-negligible sensitivity to stellar monopoles—sets a limit on the monopole density in meteoritic material of less than 2.1×10^{-5}/g at a 90% confidence level. The study analyzed 112 kg of meteorites [35], among which ~100 kg are chondrites and can thus be assumed to consist of undifferentiated material from the primary solar nebula. This represents a little more than 4 times more material than used in the present search. As discussed above, for monopole mass and charge satisfying Eq. (1) for a position above the core-mantle boundary, this difference can be compensated for by an increase in monopole concentration of roughly a factor of 6 in polar mantle-derived rocks due to monopole accumulation along Earth's magnetic axis. One can think of two ways in which these results on stellar monopoles could be further improved in the future: by probing large (>100 kg) amounts of meteorites and polar rocks with a high-efficiency magnetometer or by gaining access to new types of samples such as asteroid and comet fragments.

In summary, massive monopoles of stellar origins would be absent from planetary surfaces and would tend to accumulate along the magnetic axis in planets with internal magnetic fields. If monopoles in the mass range $10^3 \lesssim m \lesssim 10^{13}$ GeV are present within Earth, they would be expected to be found inside Earth's mantle below the geomagnetic poles. Assuming that monopoles bind strongly to nuclei, they would be trapped in mantle-derived rocks. This Letter presents the first search for monopoles in polar igneous rocks. The search probed 23.4 kg of samples, for which a limit on the monopole density of 9.8×10^{-5}/g at 90% confidence level is set, which in a simple model translates into a limit of 1.6×10^{-5}/g in the matter averaged over the whole Earth. This search has a comparable or better sensitivity than the most extensive meteorite search and provides a novel probe of stellar monopoles in the Solar System.

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*philippe.mermod@cern.ch

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