No more Valentines: New induction detectors see no monopoles

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No more Valentines: New induction detectors see no monopoles

On St. Valentine's Day two years ago, Blas Cabrera's magnetic-monopole detector at Stanford, unattended on that Sunday afternoon, recorded a current jump in its superconducting detection loop that corresponded precisely to the induction one would expect if a Dirac monopole had passed through it. "Having now expanded our monopole search almost a hundredfold with a larger, more sophisticated detector," Cabrera told us two years later to the day, "we've seen nothing comparable."

It therefore looks less and less likely, Cabrera concedes, that this one spectacular signal was indeed the calling card of a magnetic monopole. Having seen nothing in almost a year of observation with his new apparatus, whose effective collecting area (476 cm^2) is almost 50 times larger than the original prototype detector that recorded the lone spectacular candidate (PHYSICS TODAY, June 1982, page 17), Cabrera concludes that any sensible monopole search will now require a much larger collecting area. "We're all working toward football-field sized detectors," says Claudia Tesche, a member of the IBM group that has also developed a superconducting induction detector.

The heart of Cabrera's present detector is a system of three mutually orthogonal, two-turn superconducting loops, 10 cm in diameter, mounted on the surface of a single pyrex sphere. This triplet of concentric superconducting loops presents a monopole coming from a random direction with an average effective cross section of 71 cm^2 for threading at least one of the loops. An additional 405 cm^2 of effective detection area is provided by the system's capacity for detecting "near misses" that nonetheless generate persistent current vortices in the surrounding cylindrical superconducting shield.

The larger Stanford monopole detector, after a year of operation, has seen nothing like the one apparent monopole signal recorded by its smaller predecessor. Three orthogonal superconducting loops (plus a horizontal calibrating loop), each linked to a SQUID magnetometer, are wound on a 10-cm-diameter pyrex sphere.

Gradiometers. The need to shield the superconducting detection loops from fluctuations in the ambient magnetic field that could mimic the passage of a monopole is what limits superconducting induction detectors like Cabrera's to collecting areas of a few hundred cm^2. At the Monopole '82 conference, held at Racine, Wisconsin, eight months after Cabrera's candidate event had set the world abuzz, two groups proposed an ingenious scheme for freeing induction detectors of this very restrictive size limitation. The IBM group and, quite independently, Henry Frisch, a high-energy physicist at the University of Chicago, proposed to replace the simple Cabrera-type loops by elaborately twisted loops that are, by virtue of their configurations, insensitive to magnetic field fluctuations from sources other than a traversing monopole.

The simplest such "gradiometer" scheme would be a loop twisted into a figure eight, forming two smaller loops of equal area. Such a configuration is blind to any temporal variation of a uniform magnetic field because the flux links the two smaller loops in opposite senses; the emfs thus induced in the two halves of the figure eight cancel one another precisely. A monopole, on the other hand, will pass through only one half, generating its full characteristic signal. Generalizing this simple gradiometer to more complex multiloop geometries—always planar configurations arrived at by twisting a simple loop—produces inductive sensors blind to temporal variations of nonuniform fields. A twisted configuration insensitive to fluctuations in the nth spatial derivative of the ambient magnetic field is referred to as an $(n+1)$th-order gradiometer.

This gradiometer trick permits greatly increased collecting areas because it drastically reduces the shielding requirement against ambient magnetic fields. The induced current in a superconducting loop is proportional to the change in flux linking the loop, so that any noise signal due to fluctuations of the ambient field would of course be proportional to the loop area. Cabrera's complex superconducting and mu-metal shielding scheme succeeded in reducing the ambient field at the loops to a few tens of nanogauss—eight orders of magnitude below the Earth's field. Such a shielding scheme would be prohibitively demanding and costly for a much larger detector. Furthermore, a simple detecting loop must be kept well away from the superconducting shield lest the vortices generated by a monopole traversing the shield excessively degrade the signal induced in the loop. With a high-order superconducting gradiometer a simple superconducting shield remains necessary to provide some damping of fluctuations in the ambient field, but because of its insensitivity to vortices and other external sources, the antenna can come very close to the shield, making optimal use of the costly shielded cryogenic volume.

The IBM group and Frisch's Chicago–Fermilab–Michigan collaboration

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have now been running for several months, using gradiometer detectors with effective collecting areas on the order of 1000 cm^2. DOE has recently approved funding for Cabrera's plan to be on the air in about a year with a gradiometer whose effective area is some fifteen times larger than these. Note that these quoted collecting areas are effective cross sections *averaged* over all incident directions; one assumes an isotropic flux of cosmic monopoles. For a simple circular loop of geometric area A, for example, this 4π averaging yields an effective collecting area of $\frac{1}{2}A$. Three orthogonal, concentric loops, on the other hand, give an average collecting area of $\frac{7}{8}A$, almost as good as a sphere.

How can one assume an isotropic flux of monopoles when the Earth would seem to be blocking out half the solid angle? These monopoles, after all, are not neutrinos. The Dirac conjecture predicts a monopole magnetic charge of $g = e/(2\alpha)$. That is to say, a Dirac monopole at a given distance would generate a magnetic field about 70 times stronger than a relativistic electron. One could hardly neglect the ionization energy loss of such an object passing through the Earth. But if one believes the popular grand unified theories of the day, Dirac monopoles have masses in excess of 10^{16} GeV. Thus even if a massive GUTS monopole loses hundreds of MeV per cm by interacting with matter it traverses, it would take a great many Earths to put a serious dent in the kinetic energy of a monopole traveling at a speed of $10^{-3}c$.

If a monopole does indeed lose on the order of 100 MeV/cm passing through matter, one should be able to detect it by the ordinary techniques of high-energy physics, which can be applied inexpensively over very large collecting areas without the shielding and cryogenic demands of superconducting induction detectors. The rub, however, is that one knows with assurance neither the velocity spectrum of the monopoles (assuming they exist) nor how their energy loss in matter depends on velocity. It may well be that the ionization rate drops to unobservable levels just below $10^{-3}c$, the typical velocity expected for monopoles gravitationally bound by the Galaxy. In that case it would not be possible to detect the locally enhanced aggregation of slower monopoles that some have argued might be gravitationally bound in the Solar System.

Induction detectors have the virtue that they depend neither on cosmological arguments of monopole velocity nor microscopic models of interaction with matter. It requires only the macroscopic Maxwell equations to conclude that a monopole of magnetic charge g, exuding a total flux $\phi = 4\pi g$, will induce a current change of ϕ/L per turn when passing through a superconducting loop of inductance L. The persistent current change in the superconducting loop is thus a direct measure of the monopole charge, with no dependence on mass, velocity or other properties one cannot know with any confidence.

If we assume the monopole charge is given by Dirac's famous conjecture of 1931, the monopole flux becomes $2\phi_0$, where $\phi_0 = hc/2e$ is the flux quantum of superconductivity. It is not surprising that the Dirac monopole flux quantum differs from that of superconductivity by precisely a factor of two. Both are derived by imposing the requirement of single valuedness on their respective wave functions. The factor of 2 comes from the fact that the carrier of superconductivity is the *two*-electron Cooper pair. Because $2\phi_0$ is very small, about 4×10^{-7} gauss cm^2, one needs superconducting SQUID magnetometers to measure the minuscule current induced by a Dirac monopole passing through an induction detector.

Cabrera and his Stanford colleagues, Michael Taber, Robert Gardner, Martin Huber and John Bourg, having seen nothing in 214 days of low-noise running with the three-loop detector by the time of the Monopole '83 conference, held at Ann Arbor last October, reported[1] an upper limit (90% confidence level) of 2×10^{-11} cm^{-2}sec^{-1}sr^{-1} for the flux of monopoles impinging the Earth. This represents a 70-fold increase of area times time over the group's earlier observation[2] with the smaller, single-loop prototype detector. Since October, that factor has increased almost to a hundred, with still no monopoles in sight.

The three-loop detector not only provides a larger effective collecting area than its 5-cm-diameter, single-loop predecessor; it also has elaborate provision for distinguishing between a true monopole and spurious signals. "We still don't know what caused the St. Valentine's Day event," Cabrera told us, "but we're now equipped to avoid such an undecidable candidate." With three orthogonal, concentric loops, the Stanford group imposes a coincidence requirement intended to discriminate against a random noise signal in any one loop: A candidate event is considered only if it produces a current offset of greater than 0.1 ϕ_0/L in at least two of the three loops. Recall that a monopole passing through a two-turn loop produces a current change of about 4 ϕ_0/L—in general slightly washed out by the effect of the vortices the monopole generates when traversing the superconducting shield. If a monopole trajectory comes close to a loop but misses going through it, these vortices will induce a current change of a few tenths of ϕ_0/L.

The orthogonality of the three loops has been arranged with great care, Cabrera told us, so that the mutual inductance between them is negligible, insuring that signals detected in the three loops are truly independent of one another. In addition to providing a powerful coincidence filter against spurious candidates, the near-miss capacity of the system also yields a sevenfold increase in the effective collecting area of the detector. Near-miss candidates, if any had been seen, would be less convincing than a candidate that had actually threaded at least one loop, Cabrera admits. But in the absence of any near-miss signal passing the coincidence requirement, the group feels justified in including the 405 cm^2 of near-miss area (calculated by Monte Carlo simulation) in its published monopole flux limit.

Suspecting that the St. Valentine's Day candidate may have come from some mechanical disturbance of the prototype apparatus, the Stanford group monitors the present setup with an accelerometer sensitive to the mechanical resonances of the system. There are also external magnetometers to monitor excursions of the ambient field and monitors to watch for spurious signals in the SQUID loops. If there were an otherwise plausible candidate—none has been seen—one could check this array of watchdogs for a coincident non-monopole disturbance.

Cosmological limits. If one believes the argument of Eugene Parker (University of Chicago) that the presence of a 3-microgauss magnetic field throughout the Galaxy implies an upper flux limit of about 10^{-15} cm^{-2}sec^{-1}sr^{-1} for monopoles in the Galaxy, Cabrera's present limit is still four orders short of being interesting. Parker points out that monopoles accelerated to galactic escape velocity by this 3 μG field would tend to damp the currents generating the field, taking their energy out of the Galaxy. If the monopole flux exceeds 10^{-15}, he calculates, the galactic field would very quickly have been damped out of existence.

The Parker limit, corresponding to one monopole per year impinging on a 500-m^2 detector, is well beyond the reach of the induction detectors now in operation. Kenneth Lande's University of Pennsylvania group, on the other hand, will soon be on the air with a liquid-scintillator detector deep inside a South Dakota silver mine, large enough to see one monopole per two years at the Parker limit. A local enhancement of monopoles due to gravitational capture by the Sun might exceed the Parker limit by two orders of magnitude, but only at velocities too slow for such ionization detectors.

Cabrera argues that the Parker limit, while clearly appropriate for relatively light monopoles, is less convincing for the superheavy monopole predicted by the grand unified theories. Citing recent calculations by theoretical groups at Cornell[2] and Caltech,[3] he contends that GUTS monopoles would be too heavy to escape the Galaxy, spending part of their time giving energy back to the currents generating the galactic field. In that case, Cabrera suggests, the relevant limit on the flux of superheavy monopoles is the "dark" mass of the Galaxy, estimated to be about ten times its visible mass. If the monopole mass is 10^{17} GeV, for example, a flux of about 4×10^{-11} $cm^{-2}sec^{-1}sr^{-1}$ monopoles with an average velocity of $10^{-3}c$ would account for the entire hidden mass. Cabrera's group has already penetrated below this effective limit.

Frisch and his collaborators, Myron Campbell, Joe Incandela and Sunil Somalwar (Chicago), Moises Kuchnir (Fermilab) and Richard Gustafson (University of Michigan), taking the Parker bound more seriously, have set their sights on a gradiometer as large as 1000 m^2. They regard their present detector[4]—a sandwich of two gradiometer planes each with an area of 3000 cm^2—as a prototype to investigate the feasibility of a much larger detector. Thus they have eschewed any shielding scheme that would not be feasible on the large scale. A superconducting inner shield remains necessary to reduce fluctuations of the ambient field, but in place of the expensive mu-metal outer shields used by the other induction-detector groups, Frisch makes do with a simple steel shield, arguing that an ambient field on the order of 10 milligauss is acceptable. In place of ultralow ambient fields, the group has stressed the mechanical rigidity of their detector, which can be achieved much more cheaply and monitored with accelerometers and strain gauges.

The gradiometer planes are superconducting niobium wire checkerboards with equal-area cells of alternating sense. "We refer to the system as 'macramé' because we wove the originals by hand," Frisch told us. The group has thus far seen no monopole candidate in about 60 days of running.

The two-plane configuration was adopted to provide a coincidence constraint intended to compensate for the higher noise levels the group feared might accompany the higher ambient fields. But, happily, the noise levels have turned out to be sufficiently low that the group has been able to quote a monopole flux limit from the absence of single (non-coincidence) signals, in which case the effective 4π area of the detector is 1500 cm^2. This corresponds to about ⅔ of Cabrera's total exposure (area × time) to date. With the coincidence requirement, where some mono-


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poles would be lost by traversing only one plane, the effective area is only half as large, but if monopole candidates are eventually seen, Frisch explains, a coincidence signal would provide essential confirmation.

The IBM gradiometer. Tesche and her IBM colleagues, Stuart Bermon, Praveen Chaudhari, Cheng-chung Chi and Chang Tsuei, have been running since October with a system[5] of six gradiometer planes enclosing a rectangular parallelepiped, yielding a 4π-averaged collecting area of 1000 cm^2. This closed-box arrangement insures that every monopole trajectory must intersect precisely two gradiometer planes, providing an inevitable coincidence signal. A signal in only one plane or simultaneous signals in more than two planes are taken to be spurious. The detector sits in a microgauss ambient field, intermediate between Cabrera's ultralow nanogauss field and Frisch's economy-model shielding. In four months of running, the IBM detector has seen no monopole candidates, yielding a flux limit close to that published by Cabrera's group in October. "We will publish a new flux limit when we pass Cabrera's area × time, some time this spring," Tesche told us. If one combines the exposures of the three induction-detector groups as of this writing, one can say, at the 90% confidence level, that the local monopole flux does not exceed 6×10^{-12} $cm^{-2}sec^{-1}sr^{-1}$.

The IBM gradiometer pattern is more elaborate[6] than the equal-area checkerboard employed at Chicago. A complex pattern of alternating-polarity cells of varying area is precisely designed to cancel out successive terms in the Taylor-series expansion of the ambient field fluctuations. Arguing that extraneous signals from the superconducting shield would all look very much like external point sources of magnetic field, the Chicago–Fermilab–Michigan group contends that the simpler checkerboard pattern is more appropriate.

Because the current induced in the gradiometer by a monopole is inversely proportional to its inductance, which in turn is directly proportional to the total length of wire, the IBM group had developed a clever algorithm for minimizing the wire length of its elaborate gradiometer pattern. The resulting increased sensitivity lets one dispense with the amplifying transformers required by the Chicago group to link the gradiometer planes to the SQUIDS. Such superconducting transformers could be insidious sites for trapped flux, which can produce spurious signals when jumping from one pinning site to another. "But if we want to build really large detectors, "says Frisch, "we'll all have to learn to live with trapped flux." The IBM detector is immersed in liquid helium, while the Chicago–Fermilab–Michigan collaboration makes do with a vacuum environment which, they claim, will be cheaper to scale up.

A year from now the IBM group expects to be operating a new gradiometer detector with an effective collecting area thirty times that of their present system. It will, among other things, exploit the new ultrasensitive dc SQUIDS recently developed at IBM. The group is also working with collaborators at Brookhaven to explore the feasibility of a 100-m^2 gradiometer detector. —BMS

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in brief

The Tevatron at Fermilab accelerated a proton beam to 800 GeV on 15 February; the beam was then extracted and transported to an experimental area. The official Tevatron dedication is scheduled for 28 April.