current system will be set up analogous to but much smaller than that which characterizes a planetary magnetosphere. One approach toward estimating the shielded area is simply to calculate the intersection of the lunar surface with a hypothetical magnetosphere that would be produced by the model dipole. From Eq. 4, using $N_0 = 10$ cm^{-3}, $V_0 = 400$ km/sec, and $m = 2 \times 10^{16}$ G-cm^3, we find $b \cong 44$ km; this result implies that the stagnation point is roughly 12 km above the lunar surface. For comparison, $t = 1.7$ km for the same parameters. To find the surface area subtended by the magnetosphere, we take into account the tilt of the dipole by interpolation from the numerically derived surfaces of Choe *et al.* (*17*). The result is shown by the light shaded area of Fig. 2c. For the extreme values of $N_0 = 2$ cm^{-3} and $V_0 = 1000$ km/sec, we find $b \cong 36.5$ km; this value implies a more marginal standoff height of ~ 4.5 km with $t \cong 3.8$ km (dark shaded area of Fig. 2c).

Of course, the actual source of the Reiner Gamma anomaly is more probably a complex distribution of near-surface magnetization rather than a buried dipole (*6*). Higher order moments will affect both the magnetospheric surface shape and the compression of the field by varying solar wind conditions. We should therefore expect a more complex shape for the shielded region than that indicated in Fig. 2c. Strong field inhomogeneities near the surface would tend to focus and scatter incident charged particles, producing a spatially variable surface flux distribution. If the surface ion flux is a dominant determinant of surface optical properties, then an unusual albedo pattern, not unlike the swirl-like morphology of the Reiner Gamma Formation, would be produced.

L. L. HOOD
Lunar and Planetary Laboratory, University of Arizona, Tucson 85721

G. SCHUBERT
Department of Earth and Space Sciences, University of California, Los Angeles 90024

References and Notes

1. D. Matson, T. Johnson, G. Veeder, *Proc. 8th Lunar Sci. Conf.* (1977), p. 1001.
2. B. Hapke, in *Physics and Astronomy of the Moon*, Z. Kopal, Ed. (Academic Press, New York, ed. 2, 1971), p. 155; T. McCord and J. Adams, *Moon* **7**, 453 (1973).
3. Darkening of silicate rock powders by formation of hydrogen ion-sputtered glass films containing iron and titanium has been simulated in the laboratory by B. Hapke [*Moon* **7**, 342 (1973)]. A similar experiment in which the albedo of a pulverized Apollo rock sample was lowered was interpreted as due to an increase in the surface concentrations of iron and titanium by direct sputter reduction [T. Gold, E. Bilson, R. Baron, *Proc. 7th Lunar Sci. Conf.* (1976), p. 901]. Reports of other relevant experiments are discussed in the references of these papers.
4. Production of dark glass fragments by meteoroid and micrometeoroid impacts has been experimentally investigated as a possible mechanism for reducing the albedo of lunar soils by D. B. Nash, J. E. Conel, and R. T. Greer [*Science* **167**, 721 (1970)] and J. Conel and D. Nash [*Proc. Apollo 11 Lunar Sci. Conf.* (1970), p. 2013]. Differences between spectral reflectance curves for Apollo 11 and Apollo 12 soil samples were interpreted as due to variations in the amounts of impact-generated dark glass present in the soils [J. B. Adams and T. B. McCord, *Science* **171**, 567 (1971)].
5. Vapor deposits produced by solar wind sputtering or micrometeoroid impacts, or both, are considered to be the main determinant of the optical properties of the lunar surface [B. Hapke, W. Cassidy, E. Wells, *Moon* **13**, 339 (1975); E. Wells and B. Hapke, *Science* **195**, 977 (1977)]. Both solar wind exposure and agglutinate formation during micrometeoroid impacts are likely contributors to the darkening process according to R. Housley [*Philos. Trans. R. Soc. London Ser. A* **285**, 363 (1977)]. A coherent summary of the several proposed darkening mechanisms has been presented by L. Yin, T. Tsang, and I. Adler [*Geophys. Res. Lett.* **2**, 33 (1975)].
6. L. L. Hood, P. J. Coleman, Jr., D. E. Wilhelms, *Science* **204**, 53 (1979); *Proc. 10th Lunar Planet. Sci. Conf.*, in press.
6a. D. Strangway, W. Gose, G. Pearce, R. M. McConnell, *Nature (London)* **246**, 112 (1973).
7. A. Barnes, P. Cassen, J. D. Mihalov, A. Eviatar, *Science* **172**, 716 (1971); G. Siscoe and B. Goldstein, *J. Geophys. Res.* **78**, 6741 (1973).
8. P. Dyal, C. Parkin, C. Snyder, D. Clay, *Nature (London)* **236**, 381 (1972); D. Clay, B. Goldstein, M. Neugebauer, C. Snyder, *J. Geophys. Res.* **80**, 1751 (1975); L. Vanyan, *Moon* **16**, 321 (1977); P. Dyal, W. Daily, L. Vanyan, *Proc. 9th Lunar Planet. Sci. Conf.* (1978), p. 231.
9. C. Longmire, *Elementary Plasma Physics* (Interscience, New York, 1963), p. 90.
10. Gaussian units are used throughout this report.
11. P. Dyal, C. Parkin, W. Daily, *Rev. Geophys. Space Phys.* **12**, 568 (1974).
12. H. Alfvén and C. Fälthammar, *Cosmical Electrodynamics* (Oxford Univ. Press, London, 1963), p. 5.
13. G. Mead, *J. Geophys. Res.* **69**, 1181 (1964).
14. L. Hood, P. Coleman, Jr., C. Russell, D. Wilhelms, *Phys. Earth Planet Inter.* **20**, 291 (1979).
15. F. El-Baz, *NASA Spec. Publ. SP-315* (1972), p. 29:93; P. Schultz, *Moon Morphology* (Univ. of Texas Press, Austin, 1976), pp. 420–423.
16. H. Weiss, thesis, University of California, Los Angeles (1979), pp. 42–45.
17. J. Choe, D. Beard, E. Sullivan, *Planet. Space Sci.* **21**, 285 (1973).
18. We are grateful to F. Herbert for our initial interest in this problem and to C. T. Russell for enlightening criticisms. Useful discussions with C. P. Sonnett, P. J. Coleman, Jr., and D. E. Wilhelms are also acknowledged. Supported under NASA grants NSG 7020 (at the University of Arizona) and NSG 7315 (at the University of California, Los Angeles).

28 September 1979; revised 26 December 1979

Is the Sun Shrinking?

Abstract. *Observations of 23 transits of Mercury in front of the sun between 1736 and 1973 show no indication of any significant change in the diameter of the sun. Regression analysis yields a decrease of the angular diameter, as viewed from the earth, of under 0.3 arc second per century (> 90 percent confidence limit). This limit is incompatible with the 2 arc seconds per century decrease obtained by Eddy for the equatorial diameter from direct observations made at the Greenwich Observatory and at the U.S. Naval Observatory.*

Recently, Eddy (*1*) reported that the diameter of the sun, as viewed from the earth, may be decreasing at the strikingly large rate of about 2 arc seconds per century. This rate can clearly not be constant; if it were, the sun would shrink to a point in 100,000 years and would have been twice its present diameter 100,000 years ago. If, instead, this rate were periodic, with a period of centuries, its importance to our understanding of the sun would be great. I therefore sought corroborative evidence of a change in the diameter from an analysis of observations of the transits of the planet Mercury in front of the sun. These astronomical events take place about 13 times per century; they occur only in May and November, when the earth and Mercury are nearly aligned, on the same side of the sun, along the intersection of their orbital planes. Such transits have been observed regularly, with small telescopes, since the late 17th century. Traditionally, the times of up to four individual events have been recorded for each transit: the successive apparent external and internal contacts, or osculations, of the disks of Mercury and the sun (see Fig. 1). Until 30 years ago, the clocks used to time these events were based on the rotation of the earth. Because these observations consist only of the times of contact, they are virtually free from dependence on all the other variables, such as star positions, that often plague astronomical observations and their interpretation. This advantage is partially offset by the difficulty of accurately determining the instants of contact (*2*), a problem less severe for the internal contacts.

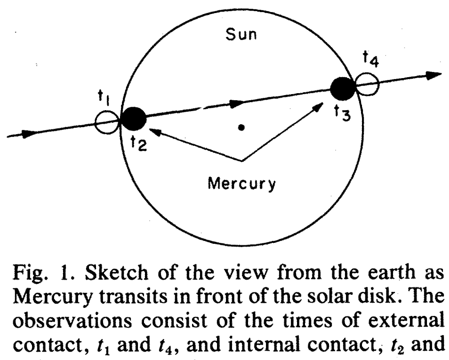

Fig. 1. Sketch of the view from the earth as Mercury transits in front of the solar disk. The observations consist of the times of external contact, t_1 and t_4, and internal contact, t_2 and t_3 ($t_1 < t_2 < t_3 < t_4$).

Primarily because of their extreme importance for the experimental foundation of the law of gravitation, the transit data

0036/8075/80/0404-0051$00.50/0

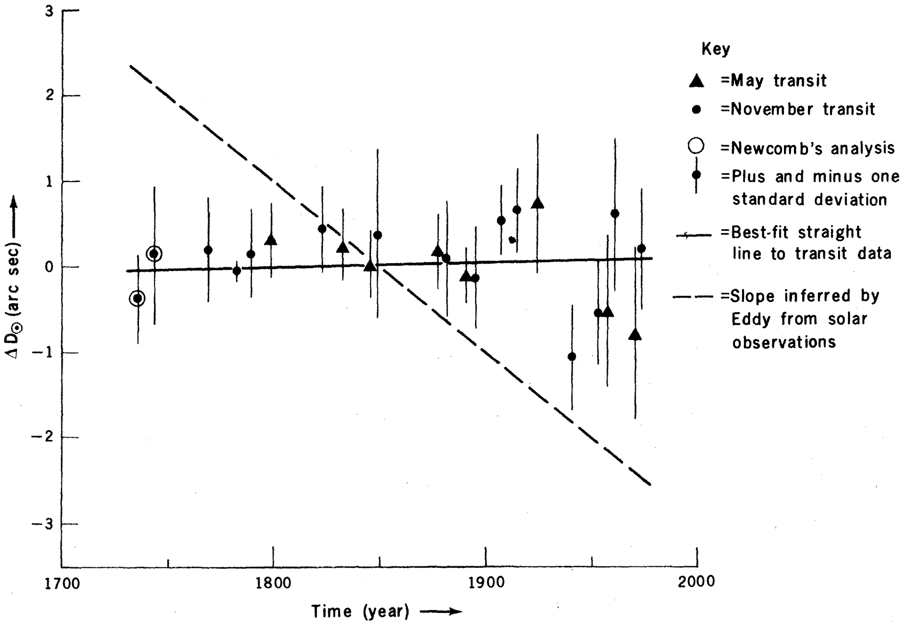

Fig. 2. Residuals from analysis of observations of Mercury transits interpreted as due to possible changes $\Delta D_\odot$ in the diameter of the sun (see text). The value $\Delta D_\odot = 0$ corresponds to $D_\odot$ = 1918.66 arc seconds; 1 arc second $\simeq$ 700 km.

have been analyzed repeatedly over the past century (*3*). For this purpose, as well as to determine variations in the rotation of the earth, Ash and I completed the first computer analysis of these data about 6 years ago (*4*). We analyzed the transit data alone and also simultaneously with nearly 300,000 other optical and radar observations of the moon and inner planets gathered between 1750 and 1973. In these analyses, many parameters were estimated, including the diameters of the sun and Mercury, which were determined by the transit data. Both diameters were assumed to be time-invariant. Thus, the differences, $\Delta t_3 - \Delta t_2$, in the postfit residuals for the internal contacts from the transit data serve as a useful measure of any variation with time in the diameter of the sun (*5*). These differences can be converted to equivalent changes, $\Delta D_\odot$, in the diameter of the sun through the easily derived relation

$$\Delta D_\odot \simeq \frac{\omega^2}{D_\odot}(t_3 - t_2)(\Delta t_3 - \Delta t_2) \quad (1)$$

where $D_\odot \simeq$ 1918.66 arc seconds is the (constant) value of the diameter, referred to a distance of 1 astronomical unit, obtained from our analysis of the transit data (*6*); ω is the apparent angular velocity of Mercury with respect to the disk of the sun, as viewed from the earth ($\omega \simeq$ 0.07 and 0.10 arc second per second, respectively, for May and November transits); and $t_3 - t_2$ is the time interval between internal contacts. The standard error, $\sigma(\Delta D_\odot)$, of each value of $\Delta D_\odot$ can be obtained from Eq. 1 by replacement of $(\Delta t_3 - \Delta t_2)$ by the root sum squares, $[\sigma^2(t_2) + \sigma^2(t_3)]^{1/2}$, of the corresponding individual standard errors of the measurements of t_2 and t_3. Figure 2 shows these values of $\Delta D_\odot$ and $\sigma(\Delta D_\odot)$ as a function of time (*7*).

The values of $\Delta D_\odot$ are free from any significant dependence on either the variation in the rotation rate of the earth or the uncertainties in knowledge of the orbital elements of the earth and Mercury and of the other pertinent solar-system parameters. To support this contention, I point out that the differences between the values of $\Delta D_\odot$ obtained from our analysis of the transit data alone, and in combination with the other data, were in each case smaller, and save for one instance much smaller, than the uncertainty due to measurement error. Since, in the analysis of the combined data sets, the transit data had virtually no effect on the estimate of any parameter, save for those of the diameters of the sun and Mercury, it follows that any variation of $D_\odot$ could not have been absorbed appreciably by compensating changes in the estimates of any of the other parameters. Thus, except for the possibility of time-dependent, systematic changes in the operational definition of instants of contact, the values of $\Delta D_\odot$ shown in Fig. 2 should display the intrinsic information on any variation of $D_\odot$ with time. The parameters of the straight line that best fits the values of $\Delta D_\odot$ were estimated by weighted least squares; the intercept, epoch 1850, and slope obtained were 0.02 ± 0.07 arc second and 0.05 ± 0.10 arc second per century, respectively (*8*). These estimates were not changed significantly either by uniformly weighting each value of $\Delta D_\odot$ or by omitting those values obtained from Newcomb's analysis (*3*). For example, these two assumptions yielded slopes of − 0.11 ± 0.14 and 0.03 ± 0.11 arc second per century, respectively. Deleting the apparently less reliable modern data, 1940 to 1973, by contrast, resulted in an estimated slope of 0.25 ± 0.10 arc second per century (*9*). Even if consideration were restricted to the case of uniform weighting of all of the data, one could conclude that any *decrease* of $D_\odot$ is under 0.3 arc second per century ($\gtrsim$ 90 percent confidence limit). Based on the corresponding, weighted-least-squares estimate of slope, one could draw the same conclusion with greater than 99 percent confidence.

This result is consistent with the conclusion reached by Sofia *et al.* (*10*) that any contemporary change in the diameter of the sun is less than 0.6 arc second per century in magnitude. But it is in serious conflict with the value of −2 arc seconds per century obtained by Eddy (*1*) for the rate of change of the equatorial diameter (*11*) from the analysis of the measurements made at the Greenwich Observatory in England and at the U.S. Naval Observatory in Washington, D.C.

I conclude that interpretations of old visual observations that depend importantly on effects discernible near the seeing limit should be treated cautiously. There are too many important questions concerning seeing, instrument characteristics, and observation techniques that are virtually unanswerable in the present era and that could bear strongly on the reliability of any interpretation.

Note added in proof: After receiving a preprint of this report, L. V. Morrison examined the residuals from his and Ward's analysis (*3*) of a more complete set of observations of transits of Mercury in front of the sun (they had searched the literature exhaustively to cull all relevant observations). From this examination, Morrison found small, as yet unexplained, differences between his results and mine for some transits [see also (*5*)], but no statistically significant change in the diameter of the sun. His weighted linear regression analysis of the residuals, whose epochs spanned the 250-year interval from 1723 to 1973, yielded a slope of − 0.14 ± 0.08 arc second per century.

IRWIN I. SHAPIRO
Department of Earth and Planetary Sciences and *Department of Physics, Massachusetts Institute of Technology, Cambridge 02139*

References and Notes

1. J. A. Eddy and A. A. Boornazian, *Am. Astron. Soc. Bull.* **11**, 437 (1979); see also *Phys. Today* **32** (No. 9), 17 (1979).
2. Seeing conditions, as well as activity near the solar limb, make very difficult the determination of the "proper" instants of contact, despite the pains taken to define these instants operationally as in the instructions distributed by the U.S. Naval Observatory to potential observers of the 1940 transit [G. M. Clemence and G. C. Whittaker, *U.S. Nav. Observatory Publ.* **15** (pt. 2), 25 (1942)]: "At the time of contact I Mercury begins to impinge on the Sun's disk. Its apparent diameter is nearly 10 seconds of arc, or about 1/200 that of the Sun. About a minute and a half later will occur a phenomenon which may be mistaken for contact II. At this instant Mercury appears to be internally tangent to the Sun's limb, but light is not yet visible all the way around the planet. This is *not* the time of contact II. About this time the black drop usually begins to form and ten seconds later Mercury will appear as a black drop hanging on the Sun's limb. Several seconds later the black drop will break away from the Sun's limb and this is the time of true contact II. At this instant a thread of light becomes visible between the planet and the Sun's limb. Although this phenomenon is perfectly well defined the time of its occurrence is often uncertain by more than ten seconds. The boiling of the Sun's limb, particularly when low in the sky, makes the observation difficult. Sometimes the thread of light appears to be made and broken several times in quick succession. In such cases the interval when it was being made and broken must be noted. In rare instances no black drop may be noticed.
"Five hours later a similar sequence of events takes place in reverse order as Mercury passes off the Sun's disk. Here the phenomenon to be observed is the breaking of the thread of light between Mercury and the Sun's limb."
3. See, for example, U. J. J. Leverrier, *Ann. Obs. Paris* **5**, 1 (1859); S. Newcomb, *Astron. Pap. Am. Ephemeris* **1** (pt. 6), 363 (1882); R. T. A. Innes, *Circ. Union Obs. S. Afr.* **65**, 303 (1925); K. P. Williams, *Indiana Univ. Publ. Sci. Ser. No. 9 and Suppl.* (1939); G. M. Clemence, *Astron. Pap. Am. Ephemeris* **11** (pt. 1), 1 (1943); L. V. Morrison and C. G. Ward, *Mon. Not. R. Astron. Soc.* **173**, 183 (1975).
4. The mean times of the contacts, for each transit through 1940, reduced to equivalent geocentric values, were obtained from earlier publications (*3*). For the last five transits, 1953 through 1973, individual observations were gathered from published accounts and analyzed by M. Ash and me (unpublished). The mean times of the contacts were treated as independent, Gaussian random variables with the standard error in each case based on the distribution of the individual observations of the time of contact. However, in no case was the standard error taken to be less than 5 seconds.
5. As an external check on our differenced residuals, $\Delta t_3 - \Delta t_2$, I compared them to the values obtained by Newcomb, by Innes, and by Williams [neither Clemence nor Morrison and Ward (*3*) reported results in a form amenable for comparison, and the overlap with the values from Leverrier was too meager to be useful]; the unweighted means of the absolute values of the differences were 3.8, 3.6, and 5.5 seconds, respectively, for the data common to our analysis and each of theirs. The corresponding means for the pairwise differences between their residuals ranged from 4.7 to 6.1 seconds. (Before making these comparisons, I changed the residuals given by Innes to correct for the time variation of the diameter of the sun obtained in his solution; see below.) It is not clear why these differences are so large, but it is clear from point-by-point comparisons that such changes in the residuals would not alter my conclusions.
6. This value is smaller than the accepted value of the diameter of the sun by about 0.6 arc second [see, for example, C. W. Allen, *Astrophysical Quantities* (Athlone, London, 1963), p. 162]. The sign of this difference could be expected on the basis of the operational definition of a transit (*2*).
7. The residuals shown for the transits observed between 1700 and 1750 were obtained from Newcomb's analysis (*3*) and are therefore not strictly compatible with the remainder of the 23, which were based on our analysis of the optical, radar, and transit data. Observations made before 1700 were deemed useless (*3*); in addition, data from 13 transits after 1700 were omitted since, for these, at most one internal contact was observed reliably (*3*). The relatively large spread in the mid-20th-century values of $\Delta D_\odot$ may be due to the far higher proportion of amateur observers for the recent than for the earlier transits and to the lack of application to the recent data (*4*) of the painstaking sorting procedure used to analyze the earlier observations. To give the flavor of the latter analysis, I quote two excerpts from Newcomb (*3*): "Looking at the general agreement among the observers of external contact, it can hardly be doubted that Mercury was entirely off the sun before 9^m0^s. If this be so, there must have been an error of half a minute or more in the times of the observers at Haarlem and The Hague. One of these is entirely unnamed, the other was not an astronomer. Their results may, therefore, be rejected without question" (p. 390). "Williams used a watch without a second hand, which was set by transits. Except for the possibility of systematic errors in the other observations, his result should be rejected. In view of this possibility, we may assign it the weight 1/3" (p. 392). The need for such extraordinary observation-by-observation analysis was dictated by the presence of systematic errors that caused the tail of the distribution of timings for most contacts to be overpopulated (platykurtic) relative to expectations based on a normal distribution.
8. The standard errors are based on a uniform scaling of the errors shown in Fig. 2 by a factor of 0.8 such that the root weighted mean square of the postfit residuals is unity.
9. Innes (*3*) also estimated the centennial change in the diameter of the sun from the transit data obtained before 1925. He found a change of 0.56 ± 0.10 arc second per century, which he attributed to the effects of the use of more powerful optics for observations of the later transits. I cannot explain the difference between Innes's results and mine as I did not attempt to reproduce his calculations.
10. S. Sofia *et al.*, *Science* **204**, 1306 (1979).
11. Eddy's analysis (*1*) actually indicated a substantial difference in the rates of change of the equatorial and polar diameters of the sun, with the former being about − 2 and the latter about − 0.8 arc second per century. In view of my far smaller bound on any change in the diameter, it seemed pointless to investigate possible differences in the rates of change of the equatorial and polar diameters from the transit data.
12. I thank F. Amuchastegui, A. Forni, and especially M. E. Ash for their important aid in the original analysis of the transit data, and C. C. Counselman, III, for a critical reading of the manuscript. This work was supported in part by NSF grant PHY 78-07760.

16 November 1979

Magnetic Field of a Nerve Impulse: First Measurements

Abstract. *The magnetic field of the action potential from an isolated frog sciatic nerve was measured by a SQUID magnetometer with a novel room-temperature pickup coil. The 1.2 × 10^{-10} tesla field was measured 1.3 millimeters from the nerve with a signal-to-noise ratio of 40 to 1.*

Although the electrical potentials produced by a propagating nerve action potential can be measured readily, the accompanying magnetic fields have thus far never been observed directly. The failure of previous attempts is readily understood. The nerve action potential has the form of a moving, azimuthally symmetric solitary wave (*1*) which can be modeled as two opposing current dipoles driven by a potential change of the order of 70 mV. The peak currents range (*2*) from 5 to 10 μA. The external magnetic

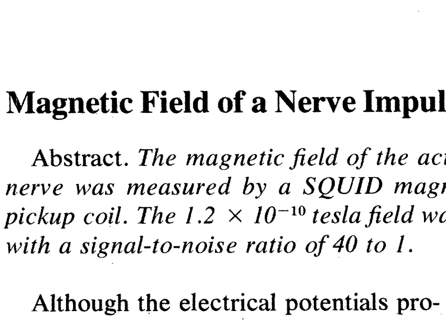

Fig. 1. Diagram of the experiment (not to scale). A nerve action potential propagates from proximal to distal (left to right in the figure). The wide and narrow arrows around the nerve represent the magnetic and electric field, respectively; the arrows on the nerve axis are equivalent dipole sources. Stimulation may be from either electrodes A or B, with the other or C as recording electrodes. The toroidal pickup coil is connected to a large transfer coil around the cylindrical Dewar vessel that contains the SQUID magnetometer and its pickup coil (indicated by dashed lines) surrounded by liquid helium.

field B can be estimated from Ampere's law, in which I is the net axial current enclosed by a closed path of integration c

$$\oint_c \mathbf{B} \cdot \mathbf{dl} = \mu_0 I \qquad (1)$$

where μ_0 is the magnetic permeability of free space, and the dot (inner) product between $\mathbf{B}$ and $\mathbf{dl}$, the differential element that describes c, is integrated over the complete length of the path.

If the nerve is immersed in a conducting medium, the maximum magnetic field of 10^{-10} T occurs at the nerve surface (radius $r \leq 0.3$ mm), with the numbers depending upon the preparation used. As the distance from the nerve is increased, an increasing fraction of the external current returns within c, so that the field at 1 cm is a few picoteslas and decreases thereafter in proportion to the inverse cube of the distance (*3*). The weakness of the magnetic field, its rapid falloff with distance, and the required 1- to 2-kHz bandwidth place the signal at the limit of detectability of magnetometers used for biomagnetic measurements (*4*).

Two groups of investigators have used large room-temperature coils and conventional amplifiers to obtain signals interpreted as the magnetic field from the action potential of an isolated frog sciatic nerve (*5*). These signals did not exhibit the expected reversal of polarity upon reversal of the direction of impulse propagation, and the measurements were

0036/8075/80/0404-0053$00.50/0