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Fumarolic Activity in Marie Byrd Land, Antarctica

Abstract. *Ice towers, probably formed by recent fumarolic activity, have been found around the summit calderas of two volcanoes in Marie Byrd Land. These active (?) volcanoes lie within a broad belt of Mesozoic intrusion and late Cenozoic extrusion that appears to be part of the circum-Pacific orogenic province.*

The Marie Byrd Land Survey (1967 to 1968) covered a coastal sector approximately 720 km long and extending up to 320 km inland, between longitudes 110°W and 136°W. The volcanic nature of many mountains in this region had been established by oversnow traverses from Byrd Station (1957 to 1958 and 1959 to 1960). One age determination from a Mount Sidley specimen, at the southern end of the Executive Committee Range, yielded an eruption date of 6.2 million years ago (*1*). We now report evidence for recent fumarolic activity in two central Marie Byrd Land mountain ranges.

Fumarolic activity in Antarctica characteristically produces ice towers by the condensation and freezing of vapors. These features have been described from observations on Mount Erebus, Ross Island, first by Shackelton (*2*) and then by Holdsworth and Ugolini (*3*). Those features forming over active fumaroles show open central vents; the inactive fumaroles on Mount Erebus are marked by ice towers without open vents. Groups of ice towers, similar in size and shape to those pictured by Holdsworth and Ugolini, were observed at close range from helicopters around the summit calderas of Mount Berlin, in the Flood Range (135°50′W, 76°03′S), and Mount Hampton, in the Executive Committee Range (125°54′W, 76°29′S). The ice towers on Mount Hampton, which were also examined from the ground, are approximately 10 to 20 m high. No open central vents or gaseous emissions were observed, and no fumarolic condensates or sublimates could be sampled because each ice structure was mantled by fresh snow. A very recent origin for these structures is almost certain, because they stand completely unprotected from wind erosion at elevations exceeding 3000 m.

Antarctic volcanoes, known to be active because of recent eruptions or geothermal activity, include Mount Erebus, on the southwestern margin of the Ross Sea; Deception Island in the South Shetland Islands; and Mount Melbourne on the Hallett Coast (*4*). Mount Morning, 90 km southwest of Ross Island, is suspected of being geothermally active on the basis of a recent infrared scan (*5*). These recently active Antarctic volcanoes lie within a large belt of late Cenozoic volcanism that extends down the Antarctic Peninsula, across Marie Byrd Land, and northward along the Hallett Coast to Cape Adare and the Balleny Islands. Granitic plutons of late Mesozoic age underlie the eastern part of this volcanic terrain, in the Antarctic Peninsula and in Ellsworth Land (*6*). The coupling of these volcanic and plutonic characteristics is typical of the circum-Pacific orogenic belt as described in more accessible and better exposed areas (*7*). It has yet to be established however, that there is a continuity of these orogenic characteristics along the full length of the Antarctic margin of the Pacific Ocean basin. The presence of ice towers on Mount Berlin and Mount Hampton suggests that there has been recent volcanic activity in Marie Byrd Land, and that the circum-Pacific orogenic belt may extend without interruption, from Ellsworth Land across Marie Byrd Land. Our tentative conclusions require confirmation by a program of infrared scanning over this entire sector, and by determinations of the ages of granitic plutons in Marie Byrd Land mountain ranges.

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Scientific Uses of Pulsars

Abstract. *The recently discovered celestial sources of pulsed radio energy can be used to test general relativity, to study the solar corona, and to determine the earth's orbit and ephemeris time. The vector positions and transverse velocities of pulsars can be measured with radio interferometers; in combination with pulse-arrival-time data, the distance determination will yield the average interstellar electron density.*

The startling discovery (*1*) and subsequent investigations (*2, 3*) of celestial objects that emit intense bursts of radio energy at regular intervals has caused great consternation (*4*) among the theorists trying to explain this phenomenon. We have not solved this theoretical problem either but, rather, wish to point out how best advantage might be taken of the existence of pulsars. In particular, we discuss several potentially important experiments that might utilize their radiation. The interpretations of such experiments are, unfortunately, dependent to some extent on the theoretical model that is assumed to describe this radiation. We therefore postulate first that pulsar emissions are perfectly regular (*5*); we also discuss models for which this assumption is invalid and consider the consequences for the proposed experiments.

A number of applications can be based on pulsars being like "one-way" radars. From accurate measurements of the times of arrival of pulses from one, or preferably more, pulsars, the orbit of the earth can be determined with standard techniques (*6*). The orbit, determined with respect to pulsar locations, can be related to optical star catalogs if pulsars can be identified with optically visible stars; otherwise, atomic-clock radio interferometry can be used to locate pulsars with respect to other point radio sources whose optical counterparts have already been identified. Is the accuracy of the orbit determination achievable with pulsars competitive with that of the standard optical and (two-way) radar methods? The answer, of course, depends on the accuracy with which the time of arrival of the pulses can be measured. At present, it appears from data obtained at Arecibo (*3*) that single-pulse arrival times can be estimated to better than 1 msec. Even this relatively modest accuracy could enable the orientation of the earth's orbital plane with respect to the stars to be determined with an error less than 0.5 arc second, which is comparable to the accuracy achievable with individual optical observations. (Two-way radar data, of course, cannot determine the orbit orientation with respect to a celestial coordinate frame.) The estimate of the motion within the orbital plane from pulsar data with 1 msec errors would be far inferior to that obtainable from the interplanetary radar data. But, by summing synchronously the pulses received during several hours (say, 10^4 pulses), the signal-to-noise ratio can be increased substantially, and the resultant pulse shape matched accurately to a standard template determined from an analysis of very long series of observations (*7*). This procedure would be quite analogous to a technique recently employed in interplanetary radar work (*8*). The signal-to-noise ratio might be further increased by recording the pulses over a very wide bandwidth and combining the results after an "anti-dispersion" operation has removed the dispersive effects of the medium between pulsar and earth observer (*9*). Although the possibility is admittedly slim, the emissions from pulsars may prove to be coherent from pulse to pulse, in which case a phase-coherent integration scheme could be employed to further increase the attainable accuracy. Phase coherence might be expected not only if the pulses were being generated artificially, but also if the pulses were being generated naturally, for example, by mode locking in a maser oscillator of light-second dimensions or by some type of beat-frequency mechanism (*1*).

The realization of even some of these possibilities may well allow the timing of pulses to be accomplished after several hours of integration with errors of 10 μsec or less (*10*). With such accuracies, the orbit of the earth could best be determined from pulsar observations.

The continual monitoring of pulse arrival times could provide an accurate and essentially instantaneous measure of "ephemeris" time. That is, given the orbit of the earth as a function of some time variable t_e, the changes in pulse arrival times due to orbital motion could be predicted, and the measurements could be used to infer t_e. Astronomers now compare special optical measurements of the moon with Brown's lunar theory for this purpose; the pulsar approach may prove more than competitive. Pulsars might also serve as an "eternal" clock in maintaining a continuous time record. Breaks in the record—provided they are not of too long duration—could be bridged by a comparison of the relative arrival times of pulses from different pulsars having incommensurable periods. The limitation on the admissible length of the gap is set, of course, by the accuracy with which the periods can be determined. Because of their very short periods, pulsars will probably be less useful as an eternal clock than the planets are.

Pulsars located near the ecliptic offer the additional possibility for studying the solar corona and for the testing of general relativity. The survey already conducted in northern declinations (*1*) has disclosed one pulsar—CP 0950—which appears to approach within 5° of the sun. The extra delay Δt_{sp} introduced by the solar plasma would be, on average (*11*)

$$\Delta t_{sp} \approx 2 \times 10^2/f^2 d \text{ second} \qquad (1)$$

where f is the frequency in megahertz at which the measurement is made and d is the distance of closest approach of the ray path to the sun, expressed in units of the sun's radius. For $f \approx$ 100 Mhz, Δt_{sp} would reach a maximum for CP 0950 of about 1 msec, which should be readily detectable even from a single pulse. Hence short-term variations in the integrated electron density through the corona could be monitored. Measurements of the polarization (*12*) of the received signals would also allow some conclusions to be drawn about the average solar magnetic field strengths along the line of sight.

Another delay effect is predicted by general relativity. According to this theory, the propagation speed of an electromagnetic wave will be slowed as it passes through the sun's gravitational field (*8, 11*). This predicted "excess" delay Δt_{sg} for pulsar emissions will vary by over 50 μsec for CP 0950 during the year, reaching its maximum when the ray path passes closest to the sun. If pulse arrival times can be distinguished with microsecond accuracy, pulsars could provide a significantly more accurate test of this general relativistic effect than has so far been possible from interplanetary radar measurements (*8*). A major advantage over the two-way radar technique is afforded by the pulse intensity being independent of the earth's position in its orbit. The radar echo intensity, on the other hand, will be weakest when Δt_{sg} is greatest. The separation of Δt_{sg} from Δt_{sp} can be accomplished easily since the former is independent of frequency whereas the latter varies with the inverse square of the received frequency. If Δt_{sg} can be determined with an error reliably under 6 percent, then the predictions of general relativity could be distinguished, for example, from those of the Brans-Dicke scalar-tensor theory (*13*) with the arbitrary parameter in the latter set in accordance with inferences made from measurements of the sun's visual oblateness (*14*). Of course, the efficacy of this test as well as of the coronal studies would be greatly enhanced if pulsars were discovered lying closer to the ecliptic. For these and other obvious reasons, an intensive search for pulsars near the ecliptic should be undertaken.

The degree of success achievable with these experiments depends, of course, on just how well actual pulsar emissions approximate the ideal of exact periodicity. We must expect the interpulse periods to have some fluctuations or slow variations due either to "imperfections" in the source mechanism, to the interstellar medium, or to a simple kinematic acceleration of the source with respect to the solar rest frame. Fluctuations of sufficiently high frequency would not interfere with most applications and, at the opposite end of the spectrum, a steady acceleration—of either sign—could be taken into account. In fact, some proposed pulsar models predict a nearly steady deceleration (*4*); although these models may well be inadequate, several other possible sources of a near-constant acceleration are important to analyze. These involve stellar dynamics (*3*) and a possible change in the gravitational constant.

If the "clock" mechanism in pulsars is controlled by the orbital period of a binary system or by the rotation period of a single massive body, then, as predicted for example by Dicke, the pulsar periods would vary because of a decrease in the gravitational "constant" G. For two-body Keplerian orbital motion, the eccentricity e is an adiabatic invariant under changes of G and the mean motion n varies according to

$$\dot{n}/n = 2\ \dot{G}/G \quad (2)$$

For G decreasing by about 3 parts in 10^{11} per year (*15*), a pulsar "clock" would lose about 1 msec/yr^2 with respect to an atomic clock in the solar rest frame. Since the earth's orbital mean motion would have the same acceleration no discrepancy would accumulate between pulsar time and "ephemeris" time (*16*).

A decrease in G would also cause a rotating mass to undergo expansion with a consequent increase in its moment of inertia; conservation of angular momentum demands that the angular velocity ω of rotation decrease accordingly. The fractional decrease in ω that would follow from a given $\dot{G}$ is unfortunately model-dependent and could vary from pulsar to pulsar. For the analytically tractable but oversimplified model in which the distribution of mass within a rotating object is determined from the equation of state $PV^\gamma =$ a constant, the equation of hydrostatic equilibrium, and Poisson's equation, we find

$$\dot{\omega}/\omega = k\ \dot{G}/G \quad (3)$$

where $k = 1$ for $\gamma = 2$. Because the constant of proportionality may depend on the object, it would be hard to infer reliably from pulsar observations, on the basis of the rotating-body hypothesis, that G is indeed changing. If a secular increase in pulsar periods were observed, then one would certainly consider $\dot{G}$ as a possible cause; but one would have to look for verification from solar-system observations. In any event, from the magnitude of any observed changes in period, an upper limit could be placed on the magnitude of any change in G.

Differential acceleration of a pulsar with respect to the sun, due to their relative orbital motions in the nonuniform gravitational field of the galaxy, would cause a secular change in the observed pulsar period (*3*). The galactic mean motion n_g in the neighborhood of the sun is about 2.5×10^{-8}/yr. Hence, a pulsar 100 parsec distant from us, in a direction either parallel or perpendicular to the direction of the galactic center and in the galactic plane, has an acceleration along our line of sight of about 4 km/yr^2, corresponding to a change in "pulsar time" relative to atomic time of about 6 μsec/yr^2. The disk-shape of the galaxy causes greater out-of-plane accelerations for comparable relative displacements out of the galactic plane. A pulsar located 50 parsec above the sun has a relative acceleration of about 17 km/yr^2. The inhomogeneity of the galactic mass density in the solar neighborhood may introduce additional relative accelerations.

If the local cluster were approximately spherical, with a density of 10^{-23} g/cm^3, and were located in a relatively low-density region of the galaxy, then relative accelerations of 6 km/yr^2 are found for stars separated radially by 50 parsec. Such galactic accelerations might be measurable from a few years of observational data, provided that the inherent pulse repetition rate of the pulsars was sufficiently stable. These accelerations are in all cases far too small to mask a change in G of the order of 3 parts in 10^{11} per year or to interfere with any of the experiments discussed above.

Finally, we point out that the vector position of nearby pulsars relative to the sun may be estimated very accurately with the use of atomic-clock radio interferometry (*17*). The direction of the pulsars can be determined in the normal manner with the distance being inferred from annual parallax. At 100 parsec this parallax will be of the order of 0.02″, whereas the potential accuracy of the interferometric technique should allow position determinations with errors of only about 0.001″. [Pulsars are effectively point sources (*18*) and emit at high enough frequencies so that neither source size nor the earth's ionosphere should create important limitations.] Furthermore, the transverse (that is, "proper") motions of these sources can also be monitored by radio interferometers.

We must also not overlook the fact that the determination from parallax measurements of the distance to pulsars allows us to make an explicit evaluation of the average interstellar electron density, rather than only the integrated electron content.

Note added in proof: A recently discovered pulsar (*19*)—PSR2045-16—passes within 1° of the sun in late January and greatly enhances the possibilities for solar plasma and general relativity experiments.

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10. At the microsecond level, account must be taken of the changing Doppler shift introduced by the motion of the observer, because this frequency shift affects the apparent time of arrival of the pulse through the dispersion in group delay caused by the propagation medium. This compensation can be accomplished easily with no accompanying degradation in accuracy.
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18. The pulse lengths imply that the typical dimension of the emission region is of the order of 5×10^3 km (*1–3*). The extraordinarily high brightness temperatures of about 10^{21} °K (*11*) imply that the emissions must be coherent.
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Magnetic Anomalies over Iceland

Abstract. *An aeromagnetic survey of Iceland reveals broad anomalies of large amplitude over zones of recent volcanic activity. The source of the anomalies is ascribed to large masses of basalt that have been coherently remagnetized by intrusive heating. A simple correlation of the Icelandic anomalies with those of the ocean floor therefore appears unjustified.*

A three-component airborne magnetic survey of Iceland was made in October 1965, as part of a larger survey extending from the west coast of Greenland to the eastern boundary of Finland. The Iceland survey was extended 350 km southeast of the island, to join the area over the Reykjanes Ridge surveyed earlier by the U.S. Naval Oceanographic Office (*1*).

From Fig. 1, it is evident that the pattern of magnetic lineations revealed over the Reykjanes Ridge by the earlier survey continues northeast to within 100 km of the south coast of Iceland. It is not immediately clear from the widely spaced profiles of Fig. 1 whether similar lineations exist in Iceland. An analysis of the space derivatives of the horizontal magnetic component indicates that the local anomalies are elongated in a preferred direction, which is northeast-southwest in the southern half of Iceland, but which becomes north-south in the northern half, changing abruptly at latitude 65°N. A more detailed survey would be required to show the magnetic lineations unequivocally, however, and we have tried to eliminate assumptions of linear magnetic structure from this discussion.

In this report we attempt to explain, as a result of crustal spreading, two characteristics of the vertical magnetic field over Iceland: (i) the occurrence of broad positive anomalies of large amplitude over the major regions of postglacial volcanic activity (Fig. 2), and (ii) the broad negative anomalies over the boundaries of the volcanic zones.

We assume that new crust is being formed beneath the main zones of volcanic activity, and hence simultaneously in two regions in southern Iceland. Geological evidence for this view is given by studies of the rate of dike injection in the active zones over the last 5000 years (*2*). Seismic evidence that the process is now occurring in the northern volcanic zone is provided by the identification of a transform fault at 66°N (*3*). We assume further that the total width of Iceland has increased at a constant rate of 2.0 cm per year over the last few million years—the same rate as the ocean floor in the vicinity of the Reykjanes Ridge (*1*).

As the first step, we apply the model of Vine and Matthews (*4*) to Iceland, and find that it leads to a violation of the second assumption of the preceding paragraph. In this model, new crust is formed near the center of an oceanic ridge, cools, and becomes magnetized in the direction of the geomagnetic field. As spreading continues and the earth's field reverses periodically, bands of normally and reversely magnetized rock spread outward symmetrically from the central axis of the ridge, to produce the linear patterns of magnetic anomalies observed over the oceans.

The polarity of the geomagnetic field has been constant for the last 0.7 million years (*5*), during which time 15 km of new crust were produced at the center of the Reykjanes Ridge, accounting for the broad positive axial anomaly. From 0.7 to 2.5 million years ago, the geomagnetic field was reversed, except for four brief intervals of normal polarity totaling 0.3 million years. If the creation of new crust had stopped 0.7 million years ago, the axis of the ridge would now be characterized by a negative anomaly in Z residuals, some 35 km wide. It is thus possible to explain the broad band of negative anomalies extending from the tip of the Reykjanes Peninsula northeast to latitude 65°N, by assuming that injection of new crust ceased there late in the last interval of reversed polarity, about 1 million years ago. The progressive change in the shape of the anomaly on the extension of the Reykjanes Ridge axis into Iceland would indicate that an eastward migration of the zone of activity had occurred at an earlier date, the closer the approach to Iceland.

The difficulty arises if one assumes that the other broad negative anomalies of southern Iceland are also due to new crust created during the last interval of reversed polarity. There is not enough new crust. The same problem exists in explaining some of the wider positive anomalies as due to spreading in the current interval of normal polarity. We are unwilling to conclude that southern Iceland is spreading several times more rapidly than the ocean floor. The difficulty could be overcome by postulating the growth and decay of many zones of activity over the last 5 million years, located so that blocks of old crust have been moved east or west, and assembled into broad bands of the required polarity. However, a demonstration with so many free parameters would be unconvincing.

We now examine three minor modifications of the Vine-Matthews model to account for the production, during an interval of constant geomagnetic polarity, of a band of anomalies with a width several times greater than the amount of crustal spreading occurring in the same time interval.

An obvious explanation is that lava extruded from a narrow zone of activity spreads horizontally over a wider region, and produces a broad anomaly after it has cooled. The objection is that the thickness of lava extruded in one polarity interval has been observed, in eastern Iceland, to be 0.2 km on the average (*6*); it cannot be much greater in the center of the island, or the pile of lavas would be much thicker than the 4 to 5 km indicated by seismic and gravity studies (*2*). It is impossible for such a thin layer, with a reasonable intensity of magnetization, to produce the anomalies observed at a height of 2 km above the surface.

A second possibility is that the broad patterns observed represent the sum of