comparison of the fusion part of the complex with the alternate use of a fast breeder reactor for this part of the job. In their "fuel factory" role, neither the fusion reactor nor the fast breeder reactor can be properly compared to an enrichment plant. Such a plant is not a synthesizer of new fissile material, but simply an extractor of dwindling natural supplies, which furthermore consumes power rather than produces it as a by-product.

The outstanding characteristic of the fusion plant is its potential ability to supply the feed and new inventory needs of many more associated thermal reactors than a fast breeder can. This advantage arises primarily from the high rate of neutron generation made possible by the relatively low energy release of the fusion event.

In considering an expanding industry, this benefit is much enhanced by the fact that the fusion plant does not require the large fissile inventory that the fast breeder requires. The importance of these features, however, rests entirely on the assumption that the thermal fission reactor will remain the best-adapted, practical prime power source, as evidenced by the costs of its construction, operation, and maintenance, by its reliability, and by its adaptability to specific needs.

If and when a pure fusion power plant can surpass the thermal fission reactor in these areas, it will doubtless displace fission altogether. In the meantime, an association of fusion and fission provides another end use for fusion (that is, as a fissile fuel factory) that must enhance the prospect of practical success. Thus, the pressure to achieve a high ratio of direct energy output to input is greatly relieved; furthermore, the function of tritium bleeding can be relegated much more conveniently to the associated fission reactors, and the need for high-temperature cooling to secure high power generation efficiency is eased. This easement might well permit use of blanket materials in aqueous solution, making possible their continuous extraction, which would represent a further, very great advantage over fast breeders, whose performance is inherently much penalized by the long element residence time of blanket materials. The "fuel factory" function is also more suited than power production to discontinuous operation, which may ease fusion plant design by allowing discontinuous plasma refueling.

All these factors could stimulate development by providing reward for early progress. Insofar as the likely result of such stimulation would be an earlier approach to the final goal of undiluted fusion, the long-range effect of an interim period in which the fusion plant is a producer of fissile fuel might well be to substantially lessen the eventual world pool of fission products.

I would emphasize that the foregoing remarks should not be construed as arguments for discarding the eventual goal of purely fusion-derived power. My intention is only to point out that, until this end is achieved, there remains a task (fissile material production) which could easily become of crucial importance to the continuity of our energy supplies, and to which fusion technology may be applied, perhaps more readily than to its ultimate objective.

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Polarity Transition Records and the Geomagnetic Dynamo

Abstract. *The Parker-Levy approach to reversals of the geomagnetic field predicts meridional transitional paths of the virtual geomagnetic pole (VGP) which pass either through the site of observation or through its antipode, depending upon the site location and the sense of the polarity transition. Comparison with the most detailed transitional VGP path records presently available gives some indication of the above behavior as predicted by the Parker-Levy model. Discrepancies may be due to complexities in the distribution of cyclonic convection cells in the core not considered in the formal mathematical treatment. The predicted variation in transitional field intensity experienced at any given site also is compatible with several reported transition records.*

The behavior of the axial dipole during a geomagnetic polarity transition is sometimes considered to consist of a simple decay followed by regeneration in the opposite sense. Such behavior is predicted by and serves to model the suggestion (*1*) that, given a Bullard-Gellman-Lilley core dynamo (*2*), field collapse occurs when the convection configuration becomes overly symmetric so as to lose the Braginskii condition (*3*). Field reversal then follows when sufficient asymmetry is restored. In contrast, the work of Parker (*4*) and of Levy (*5*) suggests that field reversals are associated with changes in the latitudinal distribution of cyclonic convection cells in the core. In contrast to the field-collapse hypothesis, the Parker-Levy reversing dynamo appears to involve a substantial conversion of the axial dipole field into axial multipole components during a polarity transition. More specifically, according to their approach, reverse toroidal flux, which acts to create a poloidal field that degenerates the existing dipole field, first appears at low latitudes. This reverse flux then extends to higher latitudes, ultimately reversing the sense of the dipole. However, when the poloidal field at low latitudes is opposite in sense to that at higher latitudes, the field experienced on the surface of the earth cannot be that of a simple dipole. A similar suggestion (Fig. 1) has been made with regard to solar field reversals (*6*).

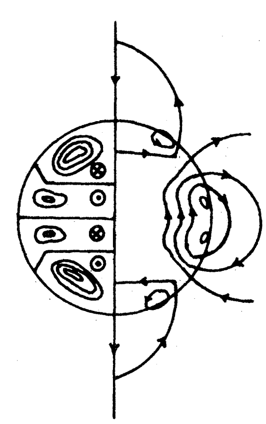


Fig. 1. An intermediate state of the solar toroidal field (at left) and the poloidal field (at right) during a reversal [after (*6*)].

One may develop a crude model of the Parker-Levy reversing dynamo by assigning for a given time at each latitude within the core an axial dipole having a sense consistent with that of the poloidal field being generated. Figure 2 depicts the sequence corresponding to a transition from reverse to normal (R → N) polarity along with the associated magnetic field vectors experienced at sites in both the Northern Hemisphere and the Southern Hemisphere.

The above models make possible the prediction of the transitional paths of the virtual geomagnetic pole (VGP) as observed at a given site. The site dependence of the predicted paths, if such exists for a given model, may then be compared with observed transitional VGP behavior inferred from paleomagnetic studies. I will follow this procedure here in an attempt to distinguish the hydromagnetic characteristics acting within the core during a field reversal.

Excluding the effect of additional nondipole field components, the decaying dipole description predicts for any site on the earth's surface an instantaneous change of the VGP from one pole to the other. In contrast, the path of the VGP obtained from the Parker-Levy approach is strongly dependent on the site of observation (Fig. 2) as well as on the sense of the transition. Except for sites along the equator or at the poles where an instantaneous change of the VGP is experienced, all paths are meridional. In particular, for sites in the Northern Hemisphere one observes great circle VGP paths passing through the site and through a point antipodal to the site for R → N and N → R transitions, respectively. For sites in the Southern Hemisphere the observation is just the opposite, with meridional paths passing through the site and through a point antipodal to the site for N → R and R → N transitions, respectively.

Paleomagnetic investigations have revealed several transitional VGP paths corresponding to a number of field reversals (*7, 8*). In particular, those transitional paths having the greatest detail and in which the effect of drifting nondipole field components is smoothed are characteristically meridional (*8–10*). Creer and Ispir (*9*) and later Steinhauser and Vincenz (*11*) concluded that such behavior is consistent with a predominantly dipolar transitional field. However, a recent comparison of records of the Matuyama-Brunhes polarity transition from California and Japan provides clear evidence to the contrary (*10*). Hillhouse and Cox (*10*) explained longitudinally constrained VGP paths in terms of a combination of a decaying dipole superposed with a stationary nondipole field component. This explanation is satisfactory, provided that the stationary nondipole field component remains so during the entire polarity transition. However, reversal of the long-term nondipole field along with the dipole field is strongly supported by recent paleomagnetic evidence (*12*). Hence, the interpretation of Hillhouse and Cox must be considered incorrect unless one arbitrarily assumes that the dipole field and the long-term nondipole field do not reverse direction simultaneously.

A test to help distinguish hydromagnetic characteristics within the core during a polarity transition is then clear. If the observed VGP paths indicate a site dependence as discussed above, the Parker-Levy reversing dynamo is supported. If the meridional paths appear to be randomly distributed with regard to the respective observation sites, then the interpretation is uncertain.

Only VGP path records possessing considerable detail within the transitional region between latitudes 45°N and 45°S were used for this study (Table 1 and Fig. 3). Unfortunately, only sites situated in the Northern Hemisphere are represented.

Unlike the paths recorded in sediments and large, slowly cooled intrusions in which each measured sample represents a finite interval of time, each

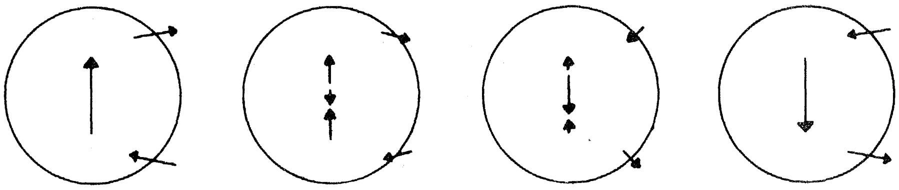


Fig. 2. Sequence corresponding to a modeled R → N transition. Magnetic field vectors at a northern latitude site and a southern latitude site are also shown. A N → R transition can be visualized simply by reversing the sense of all the vectors.

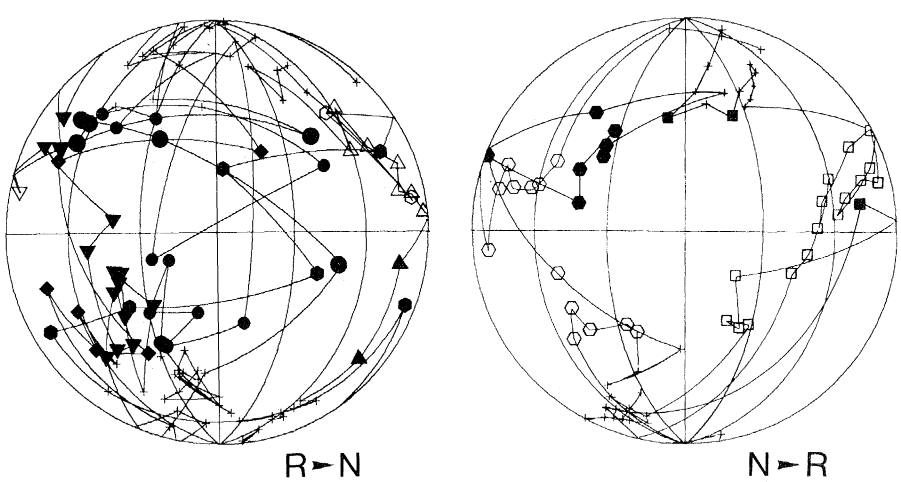


Fig. 3. Reverse-to-normal and normal-to-reverse VGP paths corresponding to the transitions listed in Table 1. Closed and open symbols represent intermediate pole positions on the upper and lower hemispheres, respectively. Crosses represent pole positions at higher latitudes. The paths are plotted with respect to the site meridian.

Table 1. Site locations and other characteristics of the detailed polarity transition records displayed in Fig. 3.

Site description	Coordinates	Age	Rock type	Sense	Reference	Symbol
Steens Mountain, Oregon	42.6°N, 119.5°W	$15.1 + 0.3 \pm 10^6$ years	Lavas	R → N	(*15*)*	●
Santa Rosa Range, Nevada	41.9°N, 117.7°W	15×10^6 years	Lavas	R → N	(*16*)*	⬢
Mount Hood, Oregon	45.5°N, 121.7°W	$8.2 \pm 0.5 \times 10^6$ years	Intrusion	R → N	(*8, 17*)	▼
Mount Rainier, Washington	46.8°N, 121.8°W	$18.0 \pm 0.5 \times 10^6$ years	Intrusion	R → N	(*13*)	◆
Boso Peninsula, Japan	35.3°N, 140.2°E	Matuyama-Brunhes	Sediments	R → N	(*18*)	●
Lake Tecopa, California	35.8°N, 117.3°W	Matuyama-Brunhes	Sediments	R → N	(*10*)	▲
Turkmenia, U.S.S.R.	39°N, 54°E†	Late Miocene	Sediments	N → R	(*19*)	⬢
Turkmenia, U.S.S.R.	39°N, 54°E†	Gauss-Matuyama	Sediments	N → R	(*19*)	■

*Thought to be the same transition. †Estimated.

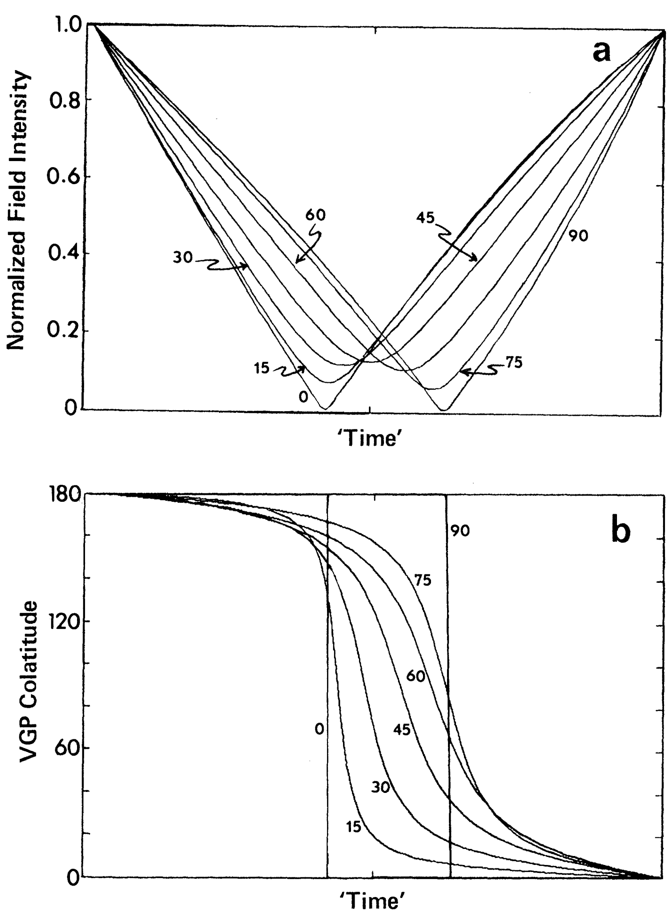
flow associated with a lava sequence represents essentially an instant in time. Hence, the magnetization vector may contain a considerable drifting component. Therefore, with respect to lavas, only paths that contain sufficient data to allow averaging over several flow units were considered.

All VGP paths corresponding to R → N transitions and N → R transitions are presented in Fig. 3 with respect to site longitude. Although the behavior predicted by the modeled Parker-Levy reversing dynamo is not strictly observed, the paths appear not to be randomly distributed in azimuth. More specifically, for VGP paths recorded at northern latitudes R → N transitions tend to appear in the hemisphere centered about the site meridian whereas N → R transitions tend to be observed in the hemisphere centered about the meridian antipodal to the site (Fig. 3). Admittedly, the N → R transition data are less convincing because of the sparse number of such paths. Nonetheless, the transitional VGP paths are supportive of the Parker-Levy model, with the following qualification. In the mathematical treatment of Parker (*4*) and Levy (*5*) it is assumed for the sake of simplicity that there is no longitudinal dependence to the distribution of cyclones at any time within the core. For the real earth, however, one expects the process to be more complicated. The effect of invoking a longitudinal dependence to the cyclonic distribution and to the generation of a reverse poloidal field is most probably to perturb the transitional VGP path from that along a particular meridian, as suggested by Fig. 3.

The Parker-Levy model may be further utilized to predict transitional field intensity as well as VGP colatitude behavior at a given site latitude as a function of relative transition time. Figure 4 shows the results corresponding to a R → N transition as observed at the indicated latitudes and clearly indicates behavior similar to that sometimes observed paleomagnetically. Specifically, decreases of intensity of from 80 to 90 percent during polarity transitions are frequently encountered. In addition, a time duration of decreased intensity approximately 2.5 times longer than that of the primary directional changes has been reported (*10, 13*). Moreover, the predicted relationship between normalized field intensity and VGP colatitude (Fig. 4c) is in general agreement with the experimental findings of Dagley and Wilson (*14*), who constructed a similar curve obtained from a large number of Tertiary lava flows on Iceland (~ 65°N). The more gradual variation of intensity with high-latitude pole positions indicated in their results may be due to the effect of drifting nondipole field sources not considered in the Parker-Levy model.

The modeled hydromagnetic Parker-Levy approach to field reversals is attractive in that it suggests both the distribution of observed, basically meridional VGP paths as well as the corresponding intensity variations to be a consequence of the transitional zonal field. Confirmation of the model, however, may rely on the existence of a site dependence for the paleomagnetic behavior. Although the few presently available detailed transitional VGP path records appear to support the model, only a small number of sites, all of which are located in the Northern Hemisphere, are represented. The individual paths considered here and several others possessing somewhat less detail are discussed in (*8*).

In view of the shortage of N → R transitional paths, a tendency for all paths recorded at northern latitudes to reside only in the hemisphere centered about the site meridian cannot be completely ruled out on the basis of the data presented here. Such a case could imply an asym-



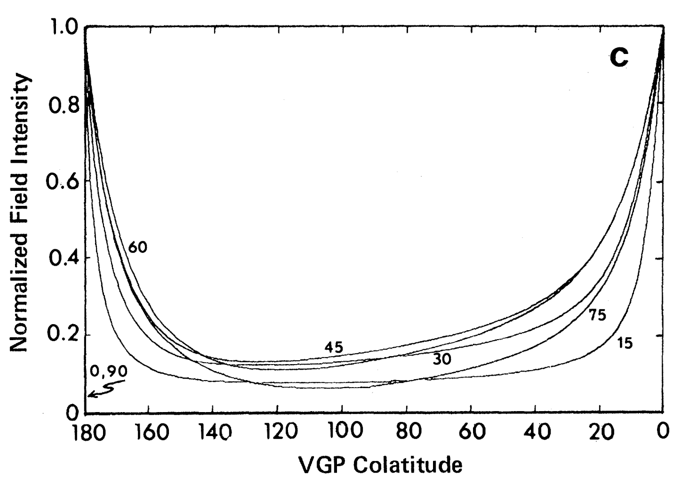


Fig. 4. Predicted transitional intensities and VGP colatitudes at the indicated (north and south) latitudes during a R → N transition. (a) Normalized field intensity versus time on an arbitrary scale; (b) VGP colatitude versus time on an arbitrary scale; (c) normalized field intensity versus VGP colatitude inferred from (a) and (b). The initial VGP colatitudes were normalized to 180°. Behavior during a N → R transition is identical in form. The calculations involve systematically reversing axial dipoles at progressively higher latitudes within the core, starting at the equator. For a given site latitude, a complete polarity transition consists of the determination of the magnetic field vector for each of 100 such zonal field configurations. The axial core dipoles were placed so as to arbitrarily extend along a distance of $0.8R_E$ (R_E = radius of the earth).

metry to the reversal process with, in particular, N → R transitions resulting from the appearance of a reverse toroidal field first at high latitudes in the core. This process may be visualized if one considers the sequence displayed in Fig. 2 to run from left to right and right to left for R → N and N → R transitions, respectively.

The model presented here, being in essence phenomenological, predicts observable behavior which need not correspond uniquely to a cyclone-driven reversal process in the core and, if substantiated, will serve primarily as a constraint to the hydromagnetic behavior governing polarity transitions.

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Lithium-Sodium Beta Alumina: First of a Family of Co-ionic Conductors?

Abstract. *Lithium-sodium beta alumina having a lithium/sodium ratio greater than about 1 appears to be the first generally useful lithium superionic conductor that has been reported. It exhibits strikingly nonlinear ion exchange properties and may presage the discovery of similar co-ionic interactions in other superionic conductors. The properties of lithium-sodium beta alumina are discussed in relation to current concepts of ionic interaction and distribution in the beta alumina conduction plane.*

Since Yao and Kummer (*1*) reported the high conductivity of Na^+ in Na^+ beta alumina, considerable effort has been directed toward identifying a comparable Li^+ conductor. Lithium is the most reducing of the alkali metals and also has the lowest equivalent weight. It is therefore attractive for use in compact and light rechargeable batteries. A high-conductivity Li^+ solid electrolyte would lend flexibility in the design of such energy storage systems.

A good Li^+ conductor has now been found in the form of Na^+ beta alumina in which a portion of the Na^+ is replaced by Li^+ (*2*). The result is a solid-solution Li^+-Na^+ beta alumina in which charge is carried by both monovalent cations. What is surprising is that the relative proportion of charge carried by each ion as a function of the Li^+/Na^+ ratio is extremely nonlinear. For compositions having Li^+/Na^+ greater than ~1, the fraction of current carried by Li^+ is nearly unity. Lithium ions move through the solid electrolyte structure without significantly altering its Na^+ content.

Numerous applications exploiting the chemical stability and high Li^+ conductivity of Li^+-Na^+ beta alumina can be imagined. But more intriguing may be the implication that similar nonlinear properties may be found generally among other superionic conductors, including those not of the beta alumina structure. We have suggested that an appropriate term for these ionic interactions would be co-ionic conductivity (*2*). Our purpose here is to report the unexpected features of Li^+-Na^+ beta alumina, their structural basis, and their implications for other co-ionic compositions.

Yao and Kummer first reported that Li^+, in addition to Ag^+, Tl^+, K^+, Rb^+, and Cs^+, can substitute for Na^+ in Na^+ beta alumina. The Li^+ exchange is curious in that a sample of pure Na^+ beta alumina equilibrated with a large excess of $LiNO_3$ at 350°C undergoes only approximately 50 percent ion exchange. The small—generally less than 0.5 percent—impurity level of Na^+ in the $LiNO_3$ melt is sufficient to maintain a Li^+/Na^+ ratio of about 1. Yao and Kummer reported preparing pure Li^+ beta alumina by equilibrating Ag^+ beta alumina, first prepared by ion exchange of Na^+ beta alumina in molten $AgNO_3$, with $LiNO_3$ saturated with LiCl.

There has been considerable disagreement over the conductivity of Li^+ beta alumina. Radzilowski *et al.* (*3*) used tracer diffusion and dielectric loss techniques to deduce the ionic conductivity of beta alumina powder in which an unspecified proportion of the Na^+ content had been replaced by Li^+. Their values, along with that reported by Whittingham and Huggins (*4*) from measurements on single crystals of beta alumina containing Li^+, are listed in Table 1. It is somewhat surprising that even though Li^+ is a smaller ion than Na^+ and might therefore be expected to diffuse more readily, the conductivity of Li^+ beta alumina is about 10 to 1400 times smaller than that of Na^+ beta alumina, which for the single-crystal form is 1.4×10^{-2} $(\text{ohm-cm})^{-1}$ at 25°C. Conductivity in Na^+ beta alumina is due to two-dimensional diffusion of Na^+ in planes that lie between close-packed oxygen layers perpendicular to the hexagonal *c*-axis (*5*). Yao and Kummer (*1*) suggested that Li^+ beta alumina is a poor conductor because Li^+ is too small for the conducting "slots" in the crystal, and as a result is displaced from the median conduction plane and attached to oxygen atoms on the wall. This explanation is consistent with measurements of the resistivity of Li^+ beta alumina as a function of pressure, which show a resistivity decrease of 5 to 6 percent at a pressure of 4 kbar (*6*).

We have examined Li^+ exchange of polycrystalline Na^+ beta alumina tubes prepared in this laboratory by a technique previously described by Powers (*7*). Our results corroborate those of Yao and Kummer. Approximately 50 percent of the Na^+ content of polycrystalline Na^+ beta alumina is replaced by Li^+ during immersion for several hours in molten $LiNO_3$ at 350° to 450°C. The composition appears to be in equilibrium with the melt, and the exchange occurs without obvious cracking or degradation of ceramic stability or strength.