field line at invariant latitude λ. For our case, z_p is much larger than z_e because the auroral field lines are approximately radial, yielding

$$I \simeq F_s \sigma_{rs} h \sin \lambda N_o \exp -[(z_e - z_o)/h \sin \lambda] \quad (4)$$

Thus, the intensity is expected to be an exponential function of the equatorward intercept z_e, and the width of the emission source is expected to be determined by the projected scale height $h \sin \lambda$.

Figure 5 shows the comparison between a modelling of the intensity according to equation (4) and the actual observations along the satellite ground track. The observed width is well fit with a scale height of ~1,000 km and, indeed, the intensity varies approximately with the equatorward intercept as an inverse exponential. The observed intensity is obtained by subtracting the fitted interplanetary hot emission background[13] from the total hot emission to obtain the magnetospheric component of the hot emisson intensity. Even without assuming any longitudinal variations of the aurora, the two intensity curves shown in Fig. 4 are sufficiently similar in shape and location to support our conjecture and to explain the most significant feature that the magnetospheric hot emission source appears to be localized. Furthermore, using the peak intensity of ~200 R and the fitted width of ~1,000 km, we can determine from equation (4) that the hot hydrogen source density is ~30 cm^{-3}. This number density is quite reasonable, as the hot H^0 includes all populations above ~0.1 eV.

We thank J. L. Bertaux for providing information on the Spacelab 1 observations.

Received 20 March; accepted 29 April 1986.

1. Chakrabarti, S., Paresce, F., Bowyer, S., Chiu, Y. T. & Aikin, A. *Geophys. Res. Lett.* **9**, 151-154 (1982).
2. Chiu, Y. T., Luhmann, J. G., Ching, B. K. & Boucher, D. J. Jr *J. geophys. Res.* **84**, 909-916 (1979).
3. Shelley, E. G. *Space Sci. Rev.* **23**, 465-497 (1979).
4. Chiu, Y. T., Cornwall, J. M., Fennell, J. F., Gorney, D. J. & Mizera, P. F. *Space Sci. Rev.* **35**, 221-257 (1983).
5. Moore, T. E. *Rev. Geophys. Space Phys.* **22**, 264 (1984).
6. Johnson, R. G. *Energetic Ion Composition in the Earth's Magnetosphere* (Reidel, Dordrecht, 1983).
7. Kumar, S., Chakrabarti, S., Paresce, F. & Bowyer, S. *J. geophys. Res.* **88**, 9271-9279 (1983).
8. Bowyer, S., Kimble, R., Paresce, F., Lampton, M. & Penegor, G. *Appl. Opt.* **20**, 477 (1981).
9. Chiu, Y. T. & Schulz, M. *J. geophys. Res.* **83**, 629-642 (1978).
10. Hoffman, J. H., Dodson, W. H., Lippincott, C. R. & Hammack, H. D. *J. geophys. Res.* **79**, 4246-4251 (1974).
11. Paresce, F., Chakrabarti, S., Boyer, S. & Kimble, R. *J. geophys. Res.* **88**, 4905-4910 (1983).
12. Chakrabarti, S., Paresce, F., Bowyer, S. & Kimble, R. *J. geophys. Res.* **88**, 4898 (1983).
13. Chakrabarti, S., Kimble, R. & Bowyer, S. *J. geophys. Res.* **89**, 5660-5664 (1984).
14. Bertaux, J. L., Goutail, F. & Kockarts, G. *Science* **225**, 174-176 (1984).
15. Heroux, L. & Hinteregger, H. E. *J. geophys. Res.* **83**, 5305-5308 (1978).

Periodicity of the Earth's magnetic reversals

Richard B. Stothers

National Aeronautics and Space Administration, Goddard Space Flight Center, Institute for Space Studies, 2880 Broadway, New York New York 10025, USA

Reversals of the Earth's magnetic field may occur with a certain regularity. Using observed percentages of normal and reversed polarity during different time intervals, Negi and Tiwari[1] detected several significant periodicities, notably one of 32–34 Myr. Raup[2] used the dates of individual reversals to propose a 30-Myr period in the frequency of reversals, although Mazaud *et al.*[3] obtained a periodicity of only 15 Myr. Like Negi and Tiwari's[1] other detected short periods, the 15-Myr period may be harmonically related to a basic 30-Myr period[4]. It has also been suggested that these are accidental periodicities arising in a short record[5,6], or are harmonics of the record length itself[7]. In fact, all of the cited studies have used different data, different record lengths and different methods of time-series analysis. Raup[8] has consequently retracted his original claim. Here I present a much fuller analyis of the reversal record and show that a statistically significant period of ~30 Myr does formally exist, in spite of the cited differences.

For consistency with the most recent studies, most of the calculations reported here have used the dates given by Harland *et al.*[9] for 296 magnetic reversals in the past 165 Myr. Raup[2] and Lutz[7] displayed histograms of these dates in bins with widths of 5 and 8.27 Myr, respectively. Because 5 Myr is a harmonic of the suggested 30-Myr period, and 8.27 Myr is too long to reveal visually a 30-Myr period, an unbiased bin width of 4 Myr is used here to construct a new histogram, shown in Fig. 1. Inspection suggests that peaking of the magnetic reversal rate near both ends of the record will produce a very strong artificial periodicity of ~140 Myr, while the complete absence of magnetic reversals near the middle of the record (Cretaceous quiet interval) will create a strong first harmonic of ~70 Myr. Superimposed on the bowl-shaped histogram, however, there appears to be a possibly real oscillation of minor peaks with a period of ~30 Myr. Other published displays of the reversal frequency suggest a shorter wavelength of 15 or 20 Myr (refs 3, 10), but only the 30-Myr oscillation appears when the data are binned in very short intervals, such as 1 Myr.

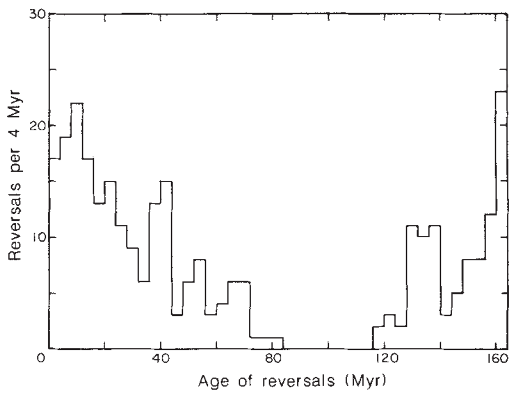

Fig. 1 Magnetic reversal frequencies shown in bins of width 4 Myr (data from ref. 9). Note the minor peaks spaced at ~30-Myr intervals.

To proceed further, the dates of individual magnetic reversals may be analysed by using a technique in which the observed dates t_i $(i = 1, 2, \ldots, N)$ are fitted to a linear periodic function of the type $t = t_0 + nP$, where P is a trial period, t_0 is a trial value for the most recent epoch, and n is an integer. In the original formulation of the technique[11], I minimized $N\sigma^2$, the sum of the squares of the residuals for each trial epoch, to obtain a best fit for a selected trial period, and computed a 'residuals index' $(\sigma - \sigma_c)/P$, where $\sigma_c/P = [(N^2-1)/12N^2]^{1/2}$. Raup and Sepkoski[12], in independent work, searched for the arithmetic mean of the residuals that was closest to zero, and Lutz[7] made a circular transformation to obtain phases of the observed data, the dispersion of which was then minimized by performing two trigonometric summations, as in Fourier analysis. Lutz's variation of the method allows a correction to be made for the unequal weighting of the dates which biases most, if not all, time-series analyses. However, as he showed that this effect is very small for the present data, I neglect it here and use the technique as originally formulated. Earlier versions, for both temporal[13] and spatial[14] problems, looked for either a least-squares or maximum-likelihood solution for two unknowns and so did not compute the spectral information, or else assumed a known value for the most recent epoch.

The computed spectrum of the residuals index for the adopted dates of magnetic reversals (Fig. 2) displays many periodicities.

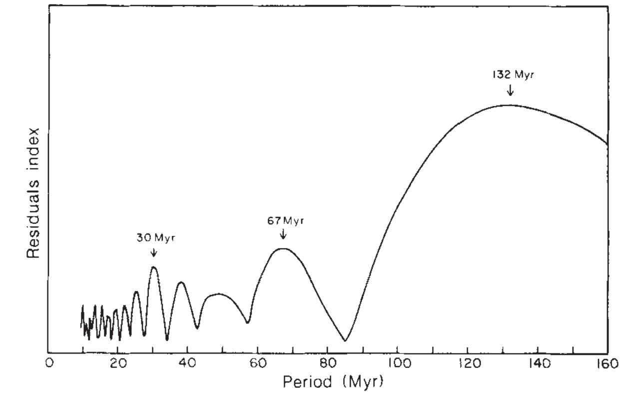

Fig. 2 Spectrum of residuals index for the complete time series of magnetic reversals, $t = 0$–165 Myr. The residuals index measures the goodness-of-fit of the observed times series to an assumed, perfectly periodic time series.

To determine their robustness, the record can be progressively truncated: successive cuts of 5 Myr are applied from the present time to as far back as 65 Myr ago (beginning of the Cenozoic Era). Table 1 lists the periods of all spectral peaks appearing at trial periods $P \geq 10$ Myr. A number of important features of this table should be noted. First, the longest period is always of the order of the length of the truncated record. (This period always has the highest spectral peak.) Second, the next-longest period is always nearly equal to one-half of the longest period. (This first-harmonic period has the next-highest spectral peak if the amount of truncation is <25 Myr.) Third, the dominant period occurring elsewhere in the computed spectra is 28–33 Myr. Its precise value oscillates down Table 1 in a discontinuous, saw-tooth fashion with a wavelength of ~30 Myr. The same wavelength of oscillation (with a slight phase shift) characterizes the neighbouring periods of 22–25 and 20–22 Myr, although the shorter periods of 18–19, 17–18 and 15–16 Myr vary down the table with a wavelength only half as large. Note that the percentage by which the period varies is smaller for the shorter periods, so that the variations of the four shortest periods, 13, 12, 11 and 10 Myr, are imperceptible. Thus, the more cycles a record contains, the less these cycles will be distorted by the record length.

The average values of the 12 periods that lie in the range 10–58 Myr are closely represented by the individual periods shown in the first row of Table 1, and are very close to what would be expected for an ideal time series consisting of six dates successively separated by 30.1 Myr. An explicit comparison of observed and expected periods is presented in Table 2, including a simple harmonic interpretation[11]. The correlation coefficient between the 11 pairs of observed and expected periods (excluding the generating period of 30.1 Myr) is $r = 0.997$. The significance of this value has been tested by correlating the sequence of 11 observed periods with 5,000 simulated sequences, each consisting of 11 numbers drawn at random from the range 10–58 Myr and then ordered. Fewer than 0.1% of the simulated sequences showed $r \geq 0.997$. Since there is no *a priori* reason to expect precisely 11 periods to show up in the range 10–58 Myr, this represents a very conservative test of significance.

An independent test has been made by generating 5,000 artificial time series, each containing 296 dates selected randomly from the time interval 0–165 Myr and then ordered. The spectrum of the residuals index has been computed for each time series and compared with Fig. 2. Fewer than 0.1% of the synthetic spectra showed a residuals index at $P = 30$ Myr that was higher than the observed peak. However, this test assumes 30 Myr as an *a priori* period and does not take into account the non-stationarities in the observed time series, as illustrated in Fig. 1.

Raup[2] performed a different significance test by randomizing the order of the observed time intervals. He found a low percentage (0.6%) of simulated cases in which the height of the observed spectral peak at $P = 30$ Myr was surpassed. Lutz[7] detected the statistical significance of the observed peaks at shorter periods, but did not recognize their harmonic connection to the 30-Myr period. Instead, he associated these periods with the record length, an interpretation that was based on a limited truncation back to only 21 Myr BP. Additional evidence against Lutz's interpretation follows from an attempt to match the provisionally expected series of harmonics (1/2, 1/3, 1/4,...) of the longest period in each row of Table 1 to the rest of the observed periods along the same row. Discrepancies of up to 15% in the values of the observed periods occur, and not all of the observed periods can be successfully identified. The number of extraneous periods per row is three in one of the rows, two in six rows, and one in another six rows; only one row has no extraneous period at all.

Truncation of the record in the middle of the Cretaceous quiet interval provides a further test. Separate spectral analyses of the more recent time segment ($t = 0$–83 Myr, $N = 196$ dates) and the older time segment ($t = 118$–165 Myr, $N = 100$ dates) yield the following results for trial periods in the range 10–40 Myr. The more recent time segment contains five spectral peaks at periods of 32.7, 20.0, 15.9, 13.3 and 9.8 Myr; the older time segment contains three peaks at 29.9, 14.2 and 10.4 Myr. For comparison, two ideal time series consisting of three dates and two dates, respectively, with generating periods of 32.7 Myr and 29.9 Myr, show high peaks only at 32.7, 21.8, 16.3, 13.1 and 10.9 Myr and only at 29.9, 14.9 and 10.0 Myr. The corresponding harmonic identifications are 1, 2/3, 1/2, 2/5 and 1/3, and 1, 1/2 and 1/3.

Table 1 Periods of the spectral peaks in time-series analyses of a progressively truncated record of magnetic reversals

t	Periods (Myr)													
0–165	132	67	48	38	30*	25	22	19	17	16	13	12	11	10
5–165	128	65	48	37	29*	24	21	19	17	15	13	12	11	10
10–165	123	63	47	36	29*	24	20	18	17	15	13	12	11	10
15–165	117	60	46	33	28*	23	20	—	18	16	13	12	11	10
20–165	113	59	44	33*	28	22	20	—	17	15	13	12	11	10
25–165	109	57	42	32*	—	25	22	19	17	15	13	12	11	10
30–165	105	55	41	30*	—	24	21	—	18	16	13	12	11	10
35–165	102	52	40	29*	—	23	20	—	17	15	13	12	11	10
40–165	99	51	38	29*	—	23	20	19	17	15	13	12	11	10
45–165	96	49	34	28*	—	22	—	—	18	16	13	12	11	10
50–165	94	48	33*	28	—	22	—	—	18	15	13	12	11	10
55–165	93	47	32*	—	—	24	—	19	17	15	13	12	11	10
60–165	93	45	31*	—	—	23	—	19	—	16	13	12	11	10
65–165	96	43	30*	—	—	23	—	18	—	15	13	12	11	10

* Highest spectral peak for periods <58 Myr.

Several conclusions can be drawn from this comparison. One is that the 15-Myr period detected by Mazaud *et al.*[3] in the more recent time segment is probably just a harmonic period, rather than the basic period. Although progressive truncation of this segment of the record back to 35 Myr BP leads, in some cases, to the highest spectral peak being at $P = 13$–15 Myr, comparison with the computed spectra of the corresponding ideal time series shows unambiguously that the generating period remains $P \simeq 30$ Myr (plus or minus the amount of period oscillation). Second, the presence of the 30-Myr period in the separate spectral analyses for $t = 0$–83 Myr and $t = 118$–165 Myr demonstrates that this periodicity is not being produced by the 35-Myr quiet interval. (Raup[2] came to the same conclusion.) Third, the abrupt shifts in the number of observed periods, going down Table 1, arise from the change in the number of cycles covered as the record is progressively truncated. For an ideal time series, the total number of integer multiples of harmonics that appear in

Table 2 Periods (Myr) of the peaks in spectral analyses of the magnetic-reversal and ideal time series

Observed series	Ideal series	Harmonic series	Harmonic series identification
48.2	48.0	45.2, 50.2	3/2, 5/3
38.0	40.5	40.1, 37.6	4/3, 5/4
30.1	30.1	30.1	1
25.2	24.0	24.1, 25.1	4/5, 5/6
—	22.0*	22.6, 21.5	3/4, 5/7
21.9	20.7	20.1, 21.5	2/3, 5/7
19.4	19.5	20.1, 18.8	2/3, 5/8
—	18.5*	18.1, 18.8	3/5, 5/8
17.2	17.3	17.2	4/7
15.5	15.1	15.1	1/2
13.4	13.1	12.9	3/7
12.0	12.0	12.0	2/5
10.9	11.0	11.3	3/8
10.0	10.0	10.0	1/3

* Very low spectral peak.

the computed spectrum is by definition controlled by the value of the largest-occurring integer, which turns out to be equal to the number of cycles covered by the time series.

Three additional checks have been made of the above results. First, Fourier analysis has been applied to the histogram shown in Fig. 1. Spectral peaks were determined to occur with relative heights and absolute periods that agreed, within the resolution of the method, with the peaks found by linear analysis. To examine the effect of the obvious non-stationarities in Fig. 1, de-trending was performed by subtracting the strongest contributing Fourier components. Accordingly, the two longest cycles, corresponding to the 132-Myr and 67-Myr periods of Fig. 2, were successively removed. Fourier analysis of the residual data then showed the highest spectral peak occurring at 30.9 Myr, which was shifted only slightly from the original value of 30.4 Myr. A similar Fourier analysis of Raup's[2] and Lutz's[7] histograms, as well as of a histogram with a 1-Myr bin width, yielded essentially identical results. This check shows that the method of analysis does not bias the results.

A second test concerned the possible influence of undetected magnetic reversals. If the unknown reversals are distributed randomly or proportionally among the known ones, their omission should not significantly affect the present results. To simulate their omission, the known magnetic reversals were systematically pruned from the record. Only the recent time segment $t = 0$–83 Myr was considered, and all fixed-polarity chrons of less than a certain length δt were excluded from the data set. As the missing chrons from the original record are probably shorter than 0.04 Myr (ref. 10), a very conservative test uses $\delta t \gg 0.04$ Myr. When $\delta t = 0.5$ Myr is used, the basic period of 30.1 Myr still emerges ($N = 49$ dates). Even with $\delta t =$ 1 Myr, the period remains 28.9 Myr ($N = 19$ dates).

A third check of the present results involved using two different sets of magnetic-reversal dates: those of Kent and Gradstein[15] ($t = 0$–169 Myr, $N = 283$ dates) and of Lowrie and Alvarez[16] ($t = 0$–84 Myr, $N = 174$ dates). Analysis of these dates by the linear technique produced the results shown in Table 3. In view of the small number of cycles covered, the differences seem rather minor, the total spread among the periods being ±3 Myr. Using maximum-entropy analysis, Pal and Creer[17] independently found the 32.1-Myr period in the data of ref. 16.

Table 3 Summary of results for the basic period (P) and phase (t_0) of magnetic reversals

Time range (Myr)	Ref. 9 dates P (Myr)	Ref. 9 dates t_0 (Myr BP)	Ref. 15 dates P	Ref. 15 dates t_0	Ref. 16 dates P	Ref. 16 dates t_0
(0-65)-170*	30.5	10	29.5	7	—	—
0-170	30.1	10	29.9	7	—	—
(0-35)-85*	28.0	14	29.0	10	28.0	14
0-85	32.7	9	28.8	7	32.1	9
115-170	29.9	10	26.9	−6	—	—

* Average of the truncation results.

The above results suggest that a real periodicity exists in the record of magnetic reversals, supporting the claims of Negi and Tiwari[1] and of Raup[2]. With fine tuning of the truncated-record results, the mean value of the basic period falls at 30.5 Myr (ref. 9 data) or 29.5 Myr (ref. 15 data). Shuter and Klatt's[18] 136-Myr period is now seen to arise only from the record length. Like the basic period, the phase oscillates in a discontinuous, saw-tooth fashion with progressive truncation, and returns to its starting value every ~30 Myr. A best estimate of its mean value is $t_0 = 10 \pm 8$ Myr BP (ref. 9 data) or $t_0 = 7 \pm 8$ Myr BP (ref. 15 data). Note that t_0 represents the most recent epoch of the mean cycle and therefore is not necessarily equal to the most recent time of high magnetic-reversal frequency, unless the times are strictly periodic.

These results do not prove that there is a physical periodicity in the Earth's magnetic record, nor do they prove that any periodicity, real or accidental, is strictly regular. However, the already demonstrated[4,19] coincidences in time between a high rate of magnetic reversals, heightened global tectonic activity, and impact cratering do at least suggest that periodic or episodic large-body impacts may trigger many of these disturbances.

I thank D. V. Kent, T. M. Lutz, P. L. McFadden, M. R. Rampino and D. M. Raup for helpful communications.

Received 9 December 1985; accepted 7 May 1986.

1. Negi, J. G. & Tiwari, R. K. *Geophys. Res. Lett.* **10**, 713-716 (1983).
2. Raup, D. M. *Nature* **314**, 341-343 (1985).
3. Mazaud, A., Laj, C., de Sèze, L. & Verosub, K. L. *Nature* **304**, 328-330 (1983).
4. Rampino, M. R. & Stothers, R. B. *Science* **226**, 1427-1431 (1984).
5. McFadden, P. L. *Nature* **311**, 396 (1984).
6. Mazaud, A., Laj, C., de Sèze, L. & Verosub, K. L. *Nature* **311**, 396 (1984).
7. Lutz, T. M. *Nature* **317**, 404-407 (1985).
8. Raup, D. M. *Nature* **317**, 384-385 (1985).
9. Harland, W. B. *et al. A Geological Time Scale* (Cambridge University Press, 1982).
10. Lowrie, W. & Kent, D. V. *Earth planet. Sci. Lett.* **62**, 305-313 (1983).
11. Stothers, R. *Astr. Astrophys.* **77**, 121-127 (1979).
12. Raup, D. M. & Sepkoski, J. J. *Proc. natn. Acad. Sci. U.S.A.* **81**, 801-805 (1984).
13. Fraser, D. A. S. *Statistics: An Introduction*, 245 (Wiley, New York, 1958).
14. Broadbent, S. R. *Biometrika* **42**, 45-57 (1955); **43**, 32-44 (1956).
15. Kent, D. V. & Gradstein, F. M. in *The Western Atlantic Region, Volume M of the Geology of North America* (eds Tucholke, B. E. & Vogt, P. R.) (Geological Society of America, Boulder, in the press).
16. Lowrie, W. & Alvarez, W. *Geology* **9**, 392-397 (1981).
17. Pal, P. C. & Creer, K. M. *Nature* **320**, 148-150 (1986).
18. Shuter, W. L. H. & Klatt, C. *Astrophys. J.* **301**, 471-477 (1986).
19. Rampino, M. R. & Stothers, R. B. *Nature* **308**, 709-712 (1984).

Thermohaline intrusions created isopycnically at oceanic fronts are inclined to isopycnals

J. D. Woods*, R. Onken & J. Fischer

Institut für Meereskunde an der Universität Kiel, FRG

Thermohaline intrusions have often been observed extending several kilometres from ocean fronts[1]. They have a central role in models of mixing[2,3]; however, their origin has been the subject of controversy. Laboratory studies led to the idea that intrusions might be formed by double diffusion[4-6], in which case they would slope across isopycnals (surface of constant density). That signature has been identified in ocean fine-structure sections[7]. Observations of the three-dimensional structure of meandering fronts led to a different conjecture: that intrusions might be formed isopycnically by the ageostrophic circulation within unstable meanders on the frontal jet[1,8]. In that conceptual model, double diffusion

* Present address: NERC, Polaris House, North Star Ave, Swindon, Wiltshire SN2 1EU, UK.