Contributions

Solar System/Geophysics/Cosmic Rays

Features of the Chandlerian Nutation

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Abstract: Reported data on the Chandlerian nutation show that there are irregular yet related changes in the rate of energy gain, the damping and the phase, changes which were remarkably great in the late 1920s. Dynamical interpretations need a model that has friction elements as well as springs and dashpots; it then offers further applications as well; e.g. to a correlation between reported values of the Love number k and tidal potentials. The model is used in discussing the increases in amplitude and the advances in phase; the short and long-term rates of energy gain and their interruptions and damping; the correlation between short Chandlerian periods and large amplitudes in the annual nutation; and the correlation between damping and the apparent frequency. Doubts are expressed about nutational values of Q. A geophysical interpretation of the model is obtained from seismic data. It was found that every large rise in the nutational energy was preceded by an earthquake in the Andes region; and that the secular rate of energy gain varied with the circum-Pacific seismicity. Decreases in these were accompanied by rises in the Earth's rotational acceleration and were followed by deep earthquakes in a diminishing region east of the Andes. It appears that the nutational and seismic events are due to tectonic stress, and intermittently this is relieved by subduction.

1. Introduction

Astronomical observations show that the changes in the characteristics of the Chandlerian nutation or wobble are too irregular to be well represented by the basic viscoelastic models, and yet the irregularities have a number of features in common (Abraham 1979). Discussion of these will first require mention of their dynamical basis and the adopted data. A note (HA) indicates that the results have been derived by the writer.

In the Chandlerian nutation the Earth's axis of figure and axis of rotation revolve freely about the angular momentum vector and about each other, with the pole of rotation P always close to the pole of angular momentum H. However, a change in the distribution of matter may displace the pole of figure F with respect to the pole of reference. The latter has been adopted close to F and P; it is determined from observations made at chosen stations which are attached to the surface of the Earth. A change in relative angular momentum may displace these stations with respect to H (and P), and crustal movements may also displace them slightly with respect to one another. Parameters which can be determined directly by astronomical observations are the semi-amplitude R, the phase $\bar{t}_0$ and their rates of change.

There is also a polar motion that progresses with respect to the pole of reference; it is shown by running 6-year mean coordinates of P, known as coordinates of the barycentre. For present purposes it is convenient to choose reference axes that, as usual, have their origin at the Earth's centre of mass, but have their x_1-axis through the meridian of date of the progressive motion, their x_2-axis 90° to the east of x_1, and the x_3-axis through the pole of reference.

2. Data

Values for the semi-amplitude R have been published by Guinot (1972) and from these the writer obtained fractional changes in time intervals $dt = 0.6$ yr. The nutational kinetic energy $E \propto R^2$, so $dE/(Edt) \propto dR/(Rdt)$; i.e. $dR/(Rdt)$ is a measure of the rate of the fractional change in the kinetic energy. Its values are shown in Figure 1(a) where they rise steeply by varying extents at irregular intervals of several years. They return less steeply, often with interruptions, to about the original level.

The writer also derived the fractional changes of R, in intervals $dt = 9$ yr. (In the original tables 9 yr forms a convenient interval). The results are shown in Figure 1(b); this has a more expanded scale and shows that there are also secular variations in $dR/(Rdt)$. It can be seen that the gradients change abruptly; in this case it is the decreases which are steep and the increases which are less steep and subject to interruptions.

The damping factor $\varkappa = -dR/(Rdt)$ by definition, when there is energy output but no energy input. Sekiguchi (1972) determined 10 yr mean values of $\varkappa$, as given in Table 1 and Figure 2, by methods that were designed to remove the effects of input. It can be seen that $\varkappa$ was not constant; in general it decayed with time but increased greatly before 1930. It was found (HA) that the rates of decrease of $dR/(Rdt)$ in Figure 1(a) and Figure 1(b) were also proportional to $\varkappa$; i.e.

$$\frac{-d}{dt}\left(\frac{dR}{Rdt}\right) \propto \varkappa.$$

The writer applied these 10 yr mean values of $\varkappa$ to the 9 yr mean values of $dR/(Rdt)$ as a rough correction for the effects of damping; then $dR/(Rdt) + \varkappa$ as in Figure 3 should be approximately proportional to the secular rate of the kinetic energy input. The figure shows that this quantity has been switching abruptly between rising and falling.

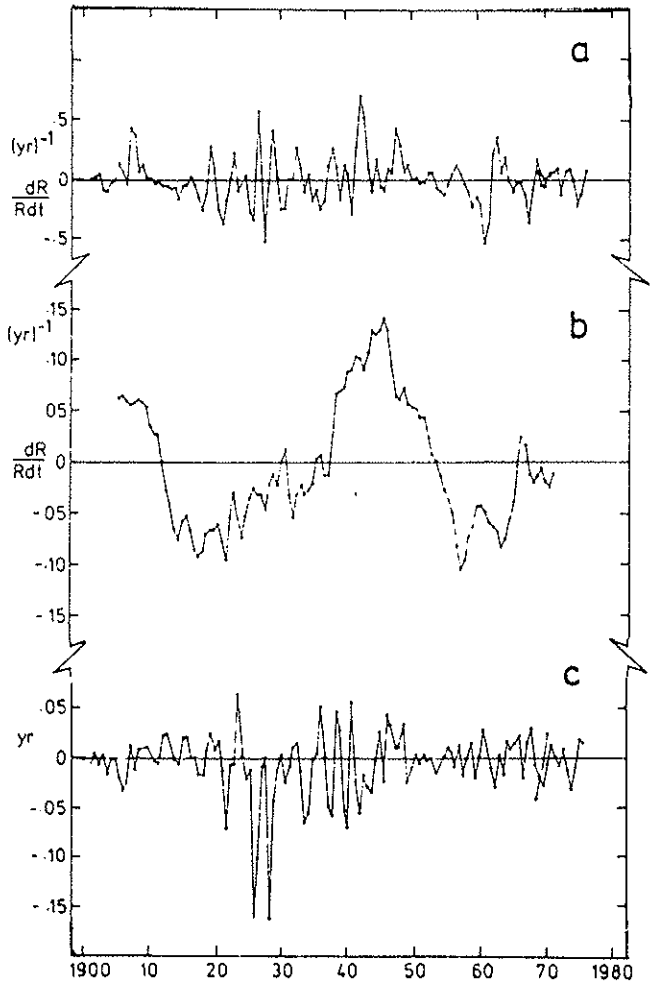

Figure 1(a) – $dR/(Rdt)$; fractional change in R per 0.6 yr; a measure of the rate of gain of kinetic energy. Calculated from Guinot (1972).
(b) – $dR/(Rdt)$; fractional change in R per 9 yr; a measure of the secular rate of gain of kinetic energy. Calculated from Guinot (1972).
(c) – Changes in phase per 0.6 yr. Calculated from Guinot (1972).

TABLE 1

$\frac{d}{dt}\left(\frac{dR}{Rdt}\right)$ AND DAMPING FACTOR κ

Interval	$\frac{d}{dt}\left(\frac{dR}{Rdt}\right)$ yr^{-2}	κ yr^{-1}	Interval	$\frac{d}{dt}\left(\frac{dR}{Rdt}\right)$ yr^{-2}	κ yr^{-1}
1910.1 to 1917.3	-.017	.017	1946.1 to 1947.3	-.056	.054
1920.3 1929.9	+.006	.074	1950.3 1956.9	-.024	.022
1930.5 1931.1	-.074	.067	1957.5 1959.3	+.030	.022
1931.1 1934.7	+.003	.067	1960.5 1963.5	-.008	.008
1940.1 1945.5	+.010	.054	1963.5 1965.9	+.041	.008

The rates of change of the 9 year values of $dR/(Rdt) + \kappa$ have also been calculated (HA) for periods when it was quiet enough for this to be done (Table 1). (Possible departures of κ from its mean values were not known so no corrections could be made for this; i.e. $d\kappa/dt = 0$.) In Figure 4 the results are plotted against κ; it was found that they fall near alternative straight lines which depend upon whether the secular value of $dR/(Rdt)$ was rising or falling. It can be seen that if $dR/(Rdt)$ was rising (i.e. if $\frac{d}{dt}\left(\frac{dR}{Rdt}\right) > 0$) the rate of rise increases as κ approaches zero and if $dR/(Rdt)$ was falling the rate of the fall tends to vanish as κ approaches zero. Moreover, it looks as though the changes in κ had more effect when $dR/(Rdt)$ was falling than when it was rising. (The observation for 1920.3-1929.9 is in doubt on account of disturbances in 1925-1929 as will be mentioned below.)

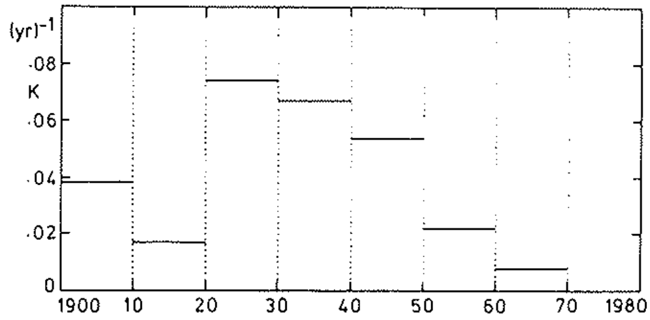

Figure 2 – Damping factor κ; 10 yr mean values (Sekiguchi 1972).

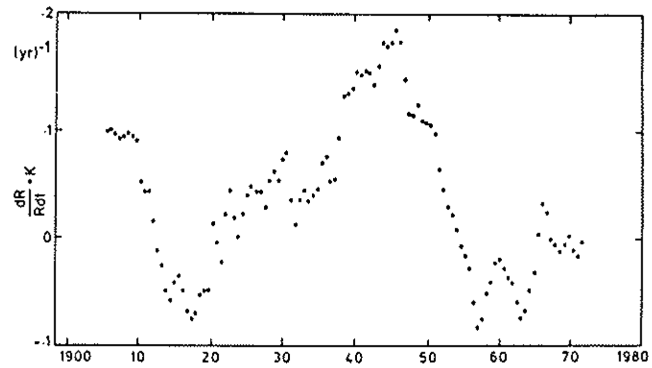

Figure 3 – $dR/(Rdt) + \kappa$; a measure of the secular rate of kinetic energy input. κ from Sekiguchi (1972), $dR/(Rdt)$ calculated from Guinot (1972).

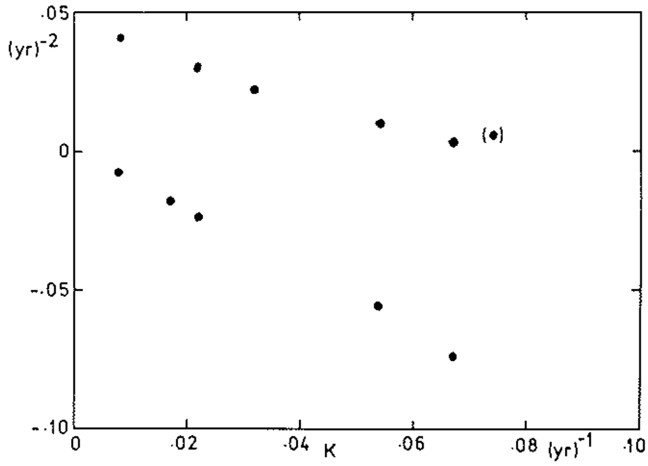

Figure 4 – Relationships between κ and secular rates of change of $dR/(Rdt)$. κ from Sekiguchi (1972), $\frac{d}{dt}\left(\frac{dR}{Rdt}\right)$ plotted on the vertical axis calculated from Guinot (1972).

TABLE 2

PHASE CHANGE $\Delta\bar{t}_o$ AND DAMPING FACTOR κ

	1900.0		1910.0		1920.0		1930.0		1940.0		1950.0		1960.0		1970.0	
$\bar{t}_o$	1905.778		1905.694		1905.764		1905.213		1905.014		1904.893		1904.862		1904.903	
$\Delta\bar{t}_o$		-0.084		+0.070		-0.551		-0.199		-0.121		-0.031		+0.041		yr
κ		0.038		0.017		0.074		0.067		0.054		0.022		0.008		yr^{-1}

Values for the phase $\bar{t}_o$ have also been published by Guinot (1972) and from these the phase changes in successive 0.6 yr intervals have been derived as well (HA). They are shown in Figure 1(c) where it can be seen that they fluctuate continually with periods of a few years and with varying amplitude. Phase changes $\Delta\bar{t}_o$ have been derived (HA) for 10 yr intervals also, as given in Table 2. (Intervals of 10 years are convenient to obtain comparisons with $\varkappa$). In general there was an exponential increase but a large fall took place before 1930. It was found (HA) that the relationship between $\Delta\bar{t}_o$ and $\varkappa$ was fairly linear, as in Figure 5, except for the period 1920 to 1930.

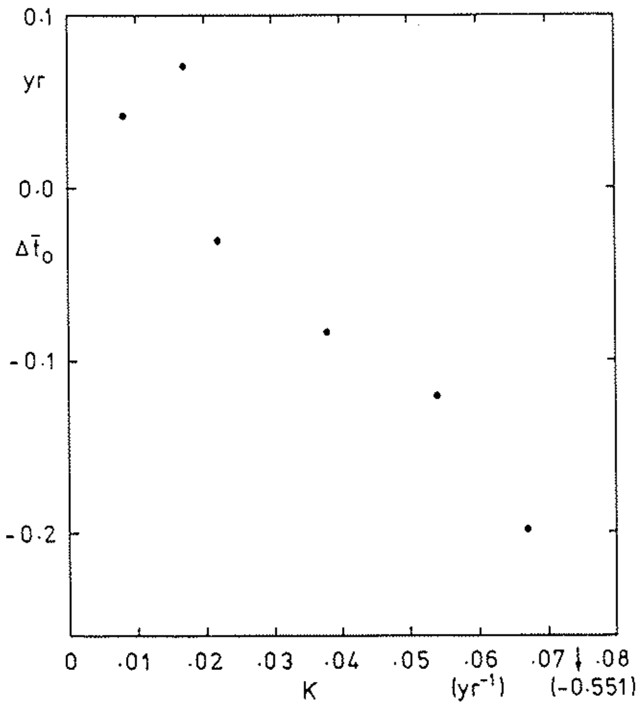

Figure 5 – Relationship between $\varkappa$ and phase changes $\Delta\bar{t}_o$ for the same 10 yr intervals. $\varkappa$ from Sekiguchi (1972), $\Delta\bar{t}_o$ calculated from Guinot (1972).

Finally, it was found (HA) that the tables for R and $\bar{t}_o$ by Guinot (1972), and for the barycentre by Yumi and Wakō (1966), all changed remarkably between about 1925 and 1929. $\bar{t}_o$ advanced by 0.166 yr at 1925.4-1926.0, and again by 0.164 yr at 1927.8-1928.4, which is nearly 1/7 cycle on each occasion. Shortly afterwards, R increased at a mean rate of 0.″028 yr^{-1} in 1926.0-1927.2, and again at 0.″033 yr^{-1} in 1928.4-1929.0. Moreover, the annual secular motion of the barycentre increased at this time; its mean value towards 90°W was 0.″00346 ± 0.″00010, yet after 1928 it became 0.″0210, 0.″0140 and 0.″0138.

3. Model

It is important to be able to refer to a general model that might reveal whether the observed results have causes in common. Fortunately, all possible geophysical effects on the motion of the Earth can be contained in excitation functions ϕ_i as explained by Munk and MacDonald (1960, p. 38), each change in ϕ_i being shown as a displacement of a pole of excitation. The behaviour of a particular excitation can then be interpreted in terms of a stress-strain model in which the ideal elastic element is the spring and the ideal viscous (time-dependent) element is the dashpot. Moreover, quite a simple model should be sufficient since one model can be equivalent to the sum of many.

However, such a viscoelastic model would behave in a regular manner, whereas, as Runcorn has argued (1970), the observed changes in phase and amplitude are far from regular. The nature of the response by actual substances commonly changes with the stress, which suggests that a geophysical change of this kind may play an important part. In that case the stress-strain model for the excitations should include friction elements too (Jaeger 1969). These have the property that if an applied stress S is less than the yield point S_o then the rate of non-elastic strain $\dot{\epsilon}$ is nil; but if $S > S_o$ then $\dot{\epsilon} \propto |S - S_o'|$. S_o depends on static friction but S_o' depends on kinetic friction and usually $S_o' < S_o$. Consequently, if S becomes greater than S_o it starts to be relieved by a slippage that continues until S decreases to S_o'. Then the opposing stress returns to S_o; S continues its growth and the process is repeated. In a coarser analogue the stress is relieved by the fracturing of a 'friction element' rather than by slippages; the drop in stress is then indefinitely great and there is a large release of energy on each such occasion.

4. Non-viscoelastic Examples

Phenomena that appear to show the effects of stresses and yield points are not uncomon so it would not be exceptional if the nutational phase and amplitude should do the same. Several examples can be mentioned.

First there is the case where successive values of S_o are relatively small so that they are exceeded in turn by S. An example is shown by the negative correlation which was found (HA) between tidal potentials and reported values of the Love number k. This can be seen in Table 3, which shows values of k that have been obtained by Guinot (1970, 1974), Pil'nik (1975) and Djurovic (1976) from tidal terms in the Earth's rotation. It also shows values of k that have been derived (HA) from data that were given by Djurovic and Melchior (1972) for the theoretical amplitudes A_c and the observed amplitudes A_o. ($k/0.317 = A_o/A_c$. The authors used alternative methods designated Fourier or Gibbs. The amplitudes A_c are quoted from Djurovic (1976). k seems to be little affected by the period of the tide.)

The apparent variation in k is taken to mean that as S grows larger only the stronger materials would not be strained to the point of non-elastic yielding. Consequently, as the tidal stresses grow larger the strain increases by a smaller fraction of the stress and k appears to get smaller.

TABLE 3

LOVE NUMBER $\underline{k}$ AND THEORETICAL TIDAL AMPLITUDE A_c

Tide (Period in days)		Mtm (9.133)	MSm (31.812)	Mf (13.661)	Mm (27.555)
Theoretical Amplitude A_c (ms)		0.32 $\underline{k}$	0.59 $\underline{k}$	2.49 $\underline{k}$	2.65 $\underline{k}$
Values of $\underline{k}$					
Djurovic & Melchior (Fourier)		0.66	0.57	0.35	0.20
Djurovic & Melchior (Gibbs)		0.61	0.57	0.35	0.26
Guinot	1970			0.331 ±0.061	0.265 ±0.068
Guinot	1974			0.334 ±0.005	0.295 ±0.011
Pil'nik	1975	0.284 ±0.133	0.404 ±0.022	0.300 ±0.015	0.282 ±0.007
Djurovic	1976			0.343 ±0.030	0.301 ±0.044

The second example concerns the case where S_o remains greater than S; here the non-elastic displacement of the fluids and/or weak solids is obstructed by strong solids, for which the values of S_o are higher. The amplitude of the pole tide in shallow and inland seas is known to be anomalously small, as was reported by Naito (1977). Then the small response in these regions may be attributed to the restricted deformation of the material that is weak.

A third example also concerns the case where S_o is greater than S, but it depends on the deformation of the solids that are strong. The nutational stress, being periodic, does not exceed a maximum amplitude; indeed in every meridian the effective value of S_o is usually greater than this, so these deformations are purely elastic. (Wherever S becomes greater than S_o damping occurs as well.) Consequently the nutational stress on its own could not remove irreversibly the matter that was helping to excite the free nutation. This kind of remanence in R can be seen in the data by Guinot (1972) where R never became less than about 0″.05.

Fourth, there is the case where S_o is very large and yet S exceeds it, as may happen when the growth of S is continual. The progressive motion of the pole shows an effect of ever-increasing excitation. If this excitation were caused by relative motions or torques they would become unacceptably large; therefore the progressive motion has been ascribed instead to progressive redistributions of matter.

5. Changes in Amplitude

In view of these examples it is of interest to apply the same model to examining the changes in R. The table by Guinot shows R as varying between about 0″.05 and 0″.29; and a table by Yumi and Wakō (1966), for example, shows that there were displacements of the barycentre; but the two tables show little correlation. This indicates that the changes in R must have come from excitations which would shift the pole of angular momentum H (and the pole of rotation P) rather than from those which would displace the barycentre.

Then there is the question as to how this could happen. The increases in R show that gains occur in the nutational kinetic energy; the continuity of the increases for several years shows that the shifts of H and P away from the barycentre are not likely to have taken place in random directions but were coordinated with the phase of the free nutation itself. Furthermore, they occurred at a phase that would make R larger. The stress that is likely to be responsible would be that which causes the deformation excitation ψ_D, since this is not only coordinated but is known to be so strong that it lengthens the nutational period from 10 months to 14. As for the source of the extra kinetic energy, the most conspicuous pointer is that offered by the progressive motion of the barycentre.

On this basis a likely stress-strain model would include a spring, dashpot and friction element and be subjected to both a periodic stress and a stress that is increasing continually. The periodic stress may modulate the continual stress and/or it may alter the effective strength of the stress that opposes it. In such a model a mounting tangential stress causes elastic deformation until S reaches an effective yield point S_o, then the slippage or fracturing takes place and a spring recoils. This would tend to happen when P is displaced in the direction of the progressive motion, since then the continual stress and the nutational stress or strain would be in the same direction.

Now the process by which R increases can be traced in terms of excitations. The barycentre advances with motion $d\phi_1/dt$ and this has already been ascribed to redistribution of matter, so $d\phi_1/dt \propto -d(x_3x_1)/dt$ (Munk and MacDonald 1960, p. 52). Therefore, when the matter springs back its motion is proportional to $d(x_3x_1)/dt$, of which possible components are x_3u_1 for the north and/or $(-x_3)(-u_1)$ for the south. Moreover, when these are impulsive they would produce an impulsive excitation ϕ_2, and this would displace P in the x_1-direction further than it is already (Munk and MacDonald 1960, p. 46). Thus P is moved away from the nutation centre and R is increased.

Two notes should be added. First, even the nutational stress on its own would have the right phase, if not the strength, to make R larger. Second, during changes in the angular momentum there would be displacements of matter as well, but their effect on the barycentre would be comparatively small.

This explanation for the growth of R applies to $dR/(Rdt)$ as well since sudden increases in R make $dR/(Rdt)$ important also. More particularly, the presence of the progressive motion implies that frictional and elastic effects are likely. On account of friction the tangential stress would rise by ∂S so that it exceeds S_o, there would be slippage or fracturing, the adjacent springs would relax and the stress would be relieved; then the process would begin once more.

Meanwhile the progressive advances of matter would also be opposed directly by increasing elastic stress and consequently the increments of strain $\partial\epsilon$ that are needed to cause ∂S would decrease exponentially. This would diminish the successive amounts of energy which are stored and then released as kinetic energy. Consequently, as shown in Figure 1(a), in the later cycles of nutation the values of $dR/(Rdt)$ would grow smaller. (It may be noted that the decreases in $dR/(Rdt)$ could also be attributed to increasingly viscous dashpots, on the grounds that less and less matter would remain to be moved and that the matter which does remain would be that which needs more force to move it.)

Figure 1(a) shows also that $dR/(Rdt)$ keeps rising sharply again to a new maximum which introduces a new series of declining values. This is attributed to the collapse of the obstruction that had been causing the increasing elastic stress, so now the applied stress is borne by the next obstruction, until several years later this too gives way. Consequently similar series of declining values of $dR/(Rdt)$ take place in succession.

This also explains why there are secular changes in $dR/(Rdt)$, as in Figure 1(b). After numerous encounters the material that is advancing would present its strongest components only. Similarly, the opposing 'friction elements' would become successively stronger and more 'work hardened' so that higher stresses would be needed to over-come them. When these higher stresses are released they cause discharges of energy that are also greater. However, in the course of time, of the order of decades, it appears that even the strongest obstruction is overcome; then the stress is relieved and continues to fall to a relatively low level, the rate depending on how quickly matter moves away.

6. Damping Factor $\varkappa$

The damping, like the growth, offers much information through the way it varies, where it occurs and the conditions that affect it. The steep rise in $\varkappa$ and its less steep decline are shown in Figure 2. It might be supposed that for some reason there had been a steep fall and less steep increase in viscosity; however, a simple explanation is offered by 'friction elements' as for the secular changes of $dR/(Rdt)$. It is presumed that mounting stress overcomes successively stronger 'friction elements' until the strongest is overcome, and then a new series of $\varkappa$ values begins. These 'friction elements', with yield stress S_o', tend to shield the dashpot (viscosity η) against the applied stress S; so $\varkappa = -dR/(Rdt) \propto |S - S_o'|/\eta$. Then the sudden rise in $\varkappa$ in the late 1920s is taken to mean that at that time there was a major fall in S_o'; this increased the effective value $S - S_o'$ of the applied stress, the rates of displacement increased and energy was dissipated faster. Several details are consistent with this. A fall in the yield stress would be likely to cause changes in angular momentum and kinetic energy; it is important, therefore, that there were indeed the exceptionally large increases in phase between 1925.4 and 1928.4 and the exceptionally rapid changes in the amplitude between 1926.0 and 1929.0. Moreover, a fall in the opposing stress would allow the progressive displacements to make an advance, as shown by the barycentre after 1928.

The variations in $\varkappa$ form such a simple pattern, as in Figure 2, that damping mechanisms appear to be statistically few. Indeed, in Figure 4 the single line when $\frac{d}{dt}\left(\frac{dR}{Rdt}\right) < 0$, and the single line when $\frac{d}{dt}\left(\frac{dR}{Rdt}\right) > 0$, are taken to mean that there are variations in only one kind of sink and source respectively. Moreover, this source is either switched right on or right off; it is evident from Figure 4 that when this input is switched off $\frac{d}{dt}\left(\frac{dR}{Rdt}\right)$ would not be greater than zero, even if the damping were nil. (However, some damping is always present.)

The damping factor $\varkappa$ is related to the rates of change of $dR/(Rdt)$, and from this it can be shown (HA) that the energy sink is related to the energy source. When $\varkappa$ grows larger the short-term and secular rates of decay of $dR/(Rdt)$ both grow larger too, but the secular rate of increase grows smaller. With regard to these traits:

(a) The short-term values of $dR/(Rdt)$ are shown in Figure 1(a) and it can be seen by inspection that $\frac{d}{dt}\left(\frac{dR}{Rdt}\right) \propto \varkappa$. The decreases in $dR/(Rdt)$ were ascribed above to advances $\partial\epsilon$ by the matter that applies the stress; so $\frac{-d}{dt}\left(\frac{dR}{Rdt}\right)$ depends upon the rate of advance of matter.

(b) The secular rate of decay of $dR/(Rdt)$, during the switched off mode, is shown by the lower line in Figure 4. The rate of fall of stress was ascribed to the rate at which matter can now move away.

(c) The secular rate of increase of $dR/(Rdt)$, which had been corrected for the damping, is shown by the upper line in Figure 4. It was ascribed to the rate at which increasingly strong 'friction elements' were being encountered.

(d) The variations in $\varkappa$ itself were ascribed to the changing strengths of 'friction elements' that retard the nutational rate of strain.

On the basis of these interpretations, the rates of decay of the rates of energy input are proportional, in both cases, to the rate at which matter is moving, either to or fro; and this motion is greater if 'friction elements' in the damping mechanism are weak. Meanwhile, the relationship between $\varkappa$ and the secular rate of increase of $dR/(Rdt)$ shows that when 'friction elements' in the damping mechanism are strong (i.e. $\varkappa$ is small), then the 'friction elements' in the input mechanism are growing rapidly stronger too. In short, the damping mechanism is closely related to the input mechanism.

7. Changes in Phase

Changes in phase have been crucial in attempts to explain the nutations, and there are many references that deal with the period or frequency. In 1948, Nicolini found that the correlation of the changes in period with the changes in amplitude was 0.88, yet this result was not confirmed in the analysis by Guinot, using further data, in 1972. Alternatively, it was shown by Sekiguchi (1972) that changes in the frequency ν would vary with changes in the damping $\varkappa$ if both ν and $\varkappa$ depend on core-mantle coupling; but in the plot of ν against $\varkappa$ the observed data showed a good deal of scatter. However, as seen from Table 2 and Figure 5, a fairly linear relationship between the 10 yr phase changes $\Delta\bar{t}_0$ and the damping factor $\varkappa$ was found by the writer when the values of $\varkappa$ by Sekiguchi were plotted against the values of $\Delta\bar{t}_0$ that had been derived (HA) from the data by Guinot (1972). (The plot for 1920-1930 is still out of line, but the published value of $\varkappa$ was for undisturbed conditions and there had been great disturbances in 1925-28.)

The observed phase changes can not be due to changes in the factors which determine the Earth's natural frequency; these would need to be unacceptably great to change the period by 27% in 1925.4-1926.0 and in 1927.8-1928.4. Moreover, the phase changes can hardly be dismissed as observational errors when comparable changes in R seem significant and are supported by seismic data as will be shown below.

Instead the phase changes can be explained from the same model as before. As previously, the barycentre's progressive motion $d\phi_1/dt$ shows that a product of inertia is changing at a rate proportional to $-d(x_3x_1)/dt$, of which possible components are $x_3(-u_1)$ in the north and/or $(-x_3)u_1$ in the south. Moreover, the values of u_1 would mainly be significant only when the nutational and progressive stresses were roughly in phase, i.e. when P was crossing the x_1 – meridian. However, while u_1 is large there would again be an appreciable excitation $-\phi_2 \propto x_3u_1$; consequently the rotation pole P would revolve about the instantaneous pole of excitation ψ-iϕ_2 instead of the usual centre at ψ. The angular speed of P about the instantaneous centre is still the same (being determined by the distribution of mass and the diurnal rotation) but its path now passes closer to ψ; therefore the phase would be advanced (but the retardations, if any, would be weak). Thus the phase advance and the apparent frequency ν have components that vary with u_1. However, u_1 and $\varkappa$ both vary with $|S\text{-}S_0'|/\eta$ and hence with each other; consequently $\partial\nu \propto \partial\varkappa$. The phase changes indicate that the *motions* u_1 are large; but the *displacements of mass* are evidently small, since $\Delta\bar{t}_0$ shows but little correlation with R or with displacements of the barycentre, even when $\Delta\bar{t}_0$ became very pronounced in the late 1920s.

It was found also (HA) that the present model leads to the correlation between short Chandlerian periods and large amplitudes in the annual nutation; this correlation has been well established by Melchior (1957), using another explanation. According to the present model when S_0' is small the values of u_1 and the advances in phase are large and so the *Chandlerian periods are short.* However, when S_0' is small then non-elastic deformations occur and so the excitation ψ_D that is caused by the elastic deformation is small. In the case of the annual nutation the forced excitation is opposed by ψ_D and so the *annual amplitude is large* when S_0' is small. Consequently, large annual amplitudes would accompany short Chandlerian periods.

8. *Q*

In determining the specific dissipation function Q^{-1} it is necessary to discriminate between changes in frequency and the effects of secular phase changes, as well as the effects of short-term changes. The consequences are of major importance because, as Stacy (1970) has pointed out, the typical value of 30 obtained from the nutations would not be compatible with the mantle being the only source of nutational energy. The value of Q depends on the widening of the spectral line being like that for a damped oscillator that is excited at random (i.e., $Q^{-1} \propto \varkappa$). In practice, if the spreading of the resonant frequency or the spreading of the apparent frequency is related to $\varkappa$ as described above, then the apparent value of Q would depend also on the distribution of $\varkappa$ (i.e. $Q^{-1} \propto \partial\varkappa$). Then determinations of Q would be inconsistent, as is indeed the case.

Furthermore, even true values of Q may depend on the stress. The values of Q that are given by free oscillations and seismic motions are of the order of 100 to 1000 and higher; however, these are due to anelastic damping, whereas in the case of the nutations there is evidence that a higher stresses energy is dissipated also by friction and fracturing. Consequently, the observed Q would partly depend on these losses as well as on the anelastic losses.

9. Nutational Changes and Earthquakes

The concept of friction elements has been useful in the non-viscous examples and numerous details of R, $\varkappa$ and $\bar{t}_0$, but their identity and location will still have to be considered. It is clear that many explanations would be possible since in principle the excitations may be due to distributions of matter, to relative motions or to torques. To restrict these options the writer looked for similar stresses and events and found that large rises in the nutational energy followed earthquakes in the Andes region.

Data about earthquakes for 1897 to 1964 were obtained from tables by Duda (1965), and for 1966 to 1974 from Unesco Annual Summaries. The data about energy increases were calculated (HA) from a table in which Guinot (1972) shows the semi-amplitude R_n for standard dates $t_n = 1900.0 + n \times 0.6$, ($n = 1, 2, \ldots$). Then the mean rate of kinetic energy increases during the interval $t_{n+1} - t_n = 0.6$ yr is proportional to $\Delta R_n = R_{n+1} - R_n$; similarly, if the rate during the interval $t_{n+2} - t_{n+1}$ is greater than this the rise in the rate of the energy increase is proportional to $\Delta^2 R_n = \Delta R_{n+1} - \Delta R_n$. Since large and infrequent quantities can be identified with more certainty Table 4 lists only the occasions when $\Delta^2 R_n \geqslant 0''.013$, and the earthquake magnitude $M \geqslant 7.9$. These events can be clearly distinguished since during 1899-1964 there were only 20 such earthquakes in the region and they took place in 15 scattered years.

Attention was drawn to the Andes by the fact that for almost a year before and after 1960.2 (which was one of the dates for $\Delta^2 R_n$) this was the only region where there were earthquakes with $M > 7.7$. Likewise for 1940.4, throughout 1940 the only earthquakes with $M > 7.75$ took place in this region also. For 1906.2, 1914.0 and 1943.4 there were other strong earthquakes but on each occasion the strongest took place in this region. For 1946.4 the strongest were also in the Andes (7.9) and in the nearby West Indies (8.1 and 7.9).

TABLE 4

RISES IN ΔR AND ANDEAN EARTHQUAKES WITH M > 7.8

t_n	$\Delta^2 R_n$ Unit 0″.01	Earthquake Date t_e	Mag.	$t_e - t_n$ Unit 1 yr	$t_{n+1} - t_e$ Unit 1 yr
1906.2	4.2	1906 Jan 31	8.9	-.1	0.7
1914.0	1.3	1914 Jan 30	8.2	+.1	.5
1918.2	3.2	1918 May 20	7.9	+.2	.4
1921.8	1.3	1921 Dec 18	7.9	+.1	.5
1940.4	2.3	1940 May 24	8.4	.0	.6
1943.4	2.5	1943 Apr 6	8.3	-.1	.7
1946.4	4.2	1946 Aug 2	7.9	+.2	.4
1960.2	2.3	1960 May 22	8.3	+.2	0.4

TABLE 5

RISES IN ΔR AND ANDEAN EARTHQUAKES WITH M < 7.8

t_n	$\Delta^2 R_n$ Unit 0″.01	Earthquake Date t_e	Mag.	$t_e - t_n$ Unit 1 yr	$t_{n+1} - t_e$ Unit 1 yr
1920.6	1.6	1920 Dec 10	7.4	+.3	0.3
1925.4	4.4	1925 May 15	7.1	.0	.6
1927.2	2.6	1927 Apr 14	7.1	+.1	.5
1927.8	2.1	1927 Nov 21	7.1	+.1	.5
1941.0	2.7	1941 Apr 3	7.1	+.2	.4
1945.2	1.7	1945 Sep 13	7.1	+.5	.1
1955.4	1.3	1955 Apr 19	7.1	+.1	.5
1958.4	1.4	1958 Jul 26	7.5	+.2	.4
1960.8	3.9	1960 Nov 1	7.2	.0	.6
1961.4	1.3	1961 Aug 31	7.5	+.3	.3
1966.8	2.2	1966 Oct 17	7.6	.0	.6
1967.4	1.7	1967 Dec 27	7.0	+.6	.0
1971.6	1.6	1971 Jul 9	7.6	-.1	.7
1974.6	1.4	1974 Aug 18	7.1	.0	0.6

Table 5 shows every remaining occasion when $\Delta^2 R_n \geqslant 0''.013$, and also the earthquake that occurred in the Andes region at about the same time. In this table $M < 7.9$ so now the risk of misidentification is greater and yet the agreement in times still has about the precision of t_{n+1}. Tables 4 and 5 show that for every entry the increase in the nutational energy had been shortly preceded by an earthquake which took place in this region. The tables also show the interval $t_{n+1} - t_e$ between the date t_e of the earthquake and the start of the tabular half-cycle of nutation for which the mean rate of energy gain had increased. Since it was the earthquakes which happened first it is clear that they were not caused by the nutational energy increases. On the other hand, the earthquakes do not appear to have been the direct cause of the energy increases either, certainly there was a tendency for the stronger earthquakes to accompany the larger values of $\Delta^2 R_n$ but not every large M was followed by a large value of $\Delta^2 R_n$. Large $\Delta^2 R_n$ and large M each often occurred in groups, and both tended to decay. Earthquakes in other regions were examined as well but coincidences with the nutational increases appeared to be accidental.

The times when the phase advanced have also been compared (HA) with the times of the earthquakes and energy increases that are listed in Tables 4 and 5. Table 6 shows every phase advance greater than 0.020 yr from 1900 to 1970, and also the intervals during which there was an earthquake (*) or a nutational energy increase (:). The columns refer to the date and to successive tabular intervals of 0.6 yr; the numbers, in units of 0.001 yr, show the changes in phase. It can be seen that some of the earthquakes which were associated with $\Delta^2 R_n$ in Tables 4 and 5 were not associated with $\Delta \ddot{t}_0$ in Table 6; likewise some $\Delta \ddot{t}_0$ were not associated with an earthquake and $\Delta^2 R_n$. On the other hand, when they were associated they followed a certain pattern closely: the interval that contained a phase advance did not occur ahead of that with the earthquakes not after that with the energy increase; and the energy increase itself came one or two intervals after the earthquake.

In interpreting this it will be recalled that for the Andes region (where $x_3 < 0$) the advances in phase were ascribed to centres of mass being rapidly displaced away from the Earth's rotation axis, in the direction of the nutational stress. The nutational energy gains, on the other hand, were ascribed to impulsive displacements of centres of mass towards the axis. Table 6 shows that the rapid displacements outwards were not always accompanied by the Andean earthquakes and nutational energy gains; nor were the latter always linked obviously with movements outwards. However, Table 6 shows as well that when such earthquakes did occur they were accompanied and usually followed by a movement outwards; and that the displacement inwards took place usually in the course of the nutational half-period that followed the earthquake. After the relapse there was, for a while, an absence of movements in either direction.

TABLE 6

MAJOR PHASE ADVANCES; AMPLITUDE INCREASE : ; ANDEAN EARTHQUAKE *

Date t_n	Change in phase per 0.6 yr t_{n-2}	t_{n-1}	t_n	Unit 0.001 yr t_{n+1}	t_{n+2}
1906.2		-34*	- 25	:	
1920.6			*	: - 71	
1925.4	-22		* -166	: -103	
1927.8			* -164	: - 43	
1930.2			- 25		
1933.2			- 66	- 56	
1936.8			- 48	- 58	
1939.2			- 52	- 70	
1941.0	-70		* - 23	: - 55	
1943.4		-29*	- 34	:	
1945.2			* - 23	:	
1948.2			- 35	- 25	
1961.4			*	: - 28	
1968.6			- 23		

Besides these relationships between individual events there are also secular relationships in the nutational and seismic activity. The secular ephemeris of $\Delta R/(R\,dt)$ in Figure 1(b) was found (HA) to resemble the figures with which Duda (1965) has represented the ephemerides of the numbers of earthquakes in the circum-Pacific region. (Seismic activity in the Kurile-Japan-Marianas region is an exception; Press and Briggs (1975) discovered that it showed negative correlation with that in the Peru-Chile region.)

Whereas the individual increases in $dR/(Rdt)$ were preceded by earthquakes in the Andes region it was found (HA) that large secular decreases in $dR/(Rdt)$ were followed by deep earthquakes further east. Figure 1(b) shows that dR/Rdt started to fall about 1907 and 1945; and Table 7 shows all the earthquakes in S. America which were listed by Duda (1965) for depths ⩾450 km in the 67 years from 1897 to 1963. It can be seen that the earthquakes were reported during the 12 years from 1911 to 1922 and the 18 years from 1946 to 1963, but not otherwise; thus they were observed in S. America only when $dR/(Rdt)$ had been falling. (Meanwhile many deep earthquakes were occurring in the world as a whole.)

TABLE 7

DEEP EARTHQUAKES IN S. AMERICA

Date	Lat. (degrees)	Long. (degrees)	Depth (km)	Mag.
1911 Apr 28	0.0 S	71.0 W	600	7.1
1912 Dec 7	29.0 S	62.5 W	620	7.5
1915 Apr 23	8.0 S	68.0 W	650	7.25
1916 June 21	28.5 S	63.0 W	600	7.5
1921 Dec 18	2.5 S	71.0 W	650	7.9
1922 Jan 17	2.5 S	71.0 W	650	7.6
1946 Aug 28	26.0 S	63.0 W	580	7.2
1947 Jan 29	26.0 S	63.0 W	580	7.25
1950 Jul 9	8.0 S	70.8 W	650	7.0
1950 Jul 9	8.0 S	70.8 W	650	7.0
1950 Aug 14	27.3 S	62.5 W	630	7.25
1958 Jul 26	13.5 S	69.0 W	620	7.5
1961 Aug 19	10.8 S	71.0 W	649	7.0
1961 Aug 31	10.7 S	70.9 W	626	7.2
1961 Aug 31	10.5 S	70.7 W	629	7.5
1963 Aug 15	13.8 S	69.3 W	543	7.75
1963 Nov 9	9.0 S	71.5 W	600	7.0

The region of these earthquakes has grown smaller. When plotted on the map they form three lines, all well to the east of the Andes. In 1911-22 they extended 29° of latitude, in 1946-50 they were nearer the Andes and extended less than 20°, while in 1958-63 they were nearer still and extended hardly 5°. The sample is small; however it is consistent with the view that the nutational and seismic energy falls when stress from the Pacific is relieved by the movement of material towards the east and downwards.

It was found (HA) that these falls in the secular values of $dR/(Rdt)$ were accompanied as well by increasing values of $\dot{\omega}$, the acceleration of the Earth's rotation. This acceleration would cause UT to gain annually by $\partial(\mathrm{UT}) = \partial(\mathrm{ET} - \Delta t) = -\partial(\Delta T)$; so $-\partial(\Delta T) \propto \dot{\omega}$. Running 10 year mean annual values of $-\partial(\Delta T)$ were derived (HA) from The Explanatory Supplement of the Astronomical Ephemeris (1974). Figure 6 shows that these values started to rise about 1907 and 1945, which was when $dR/(Rdt)$ was starting to fall. Thus $dR/(Rdt)$ and $\dot{\omega}$ show negative correlation.

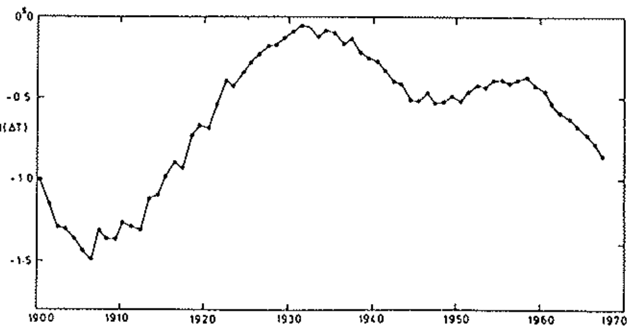

Figure 6— $-\partial(\Delta T)$, 10 yr mean annual values; a measure of the Earth's rotational acceleration $\dot{\omega}$. Calculated from Explanatory Supplement to the Astronomical Ephemeris (1974).

It can be shown that this is consistent with seismic evidence also, as mentioned previously, the correlation between the secular values of $dR/(Rdt)$ and Duda's ephemerides of seismicity is positive; therefore the correlation between $\dot{\omega}$ and the seismicity should be negative. Press and Briggs (1975) did, in fact, find that seismicity was small when $\dot{\omega}$ was large.

10. Conclusions

Many irregularities in R, $\varkappa$ and $\bar{t}_0$, and perhaps in $\dot{\omega}$, are not accidental; they are effects of stress. They can be combined with one another and with seismic activity by reference to an excitation model in common (but in principle every irregularity can have alternative geophysical explanations). Reported values of k that were obtained from tidal terms in the Earth's rotation are stress dependent.

In the Andes region subduction is obstructed by the continent itself but is periodically assisted by nutational stresses. Brief but rapid increases in the products of inertia in that region cause the nutational phase to advance. The opposing stress is relieved intermittently by displacements that have components towards the Earth's rotation axis. When these are impulsive they cause gains in the nutational kinetic energy. As the stress that opposes the tectonic advance grows greater the energy gains grow smaller; and when the obstruction gives way this process begins again. However, in the course of several years the strength of successive obstructions increases; consequently the peaks of the energy gain rise likewise. In a typical pattern of events, when the obstruction gives way there are earthquakes and the phase keeps advancing; next the nutational energy rises sharply and then, temporarily, the phase advances cease.

The nutational damping mechanism is related closely to the input mechanism. The damping is caused by retarding stresses which become effectively weaker; this is due to obstructions that become successively stronger but are eventually overcome. Strong obstructions are associated with a small rate of nutational energy output, a small rate of decay of the short-term rate of energy input, and a small rate of fall and a large rate of increase in the secular rate of energy input. Weak obstructions in the damping mechanism would lead to a short Chandlerian period and a large amplitude of the annual nutation. Values of Q that are derived from the range of frequency would depend on the distribution of the damping as well as on the damping itself.

Occasionally the tectonic stress achieves a major advance and extends inland to greater depths; this relieves stresses not only in the Andes region but around the Pacific.

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Postscript on 'Features of the Chandlerian Nutation',

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Henry Abraham died on 9 December 1985. A few days earlier, he explained to me the work he had been doing in recent years, and gave me responsibility for his documents and notes. Amongst them were the manuscript for the above paper, prepared about 1979 but not submitted for publication then, and meticulous and extensive notes which examine further the questions raised by the paper. It has seemed to me to be appropriate to submit for publication the above paper as he wrote it, and to add a summary of his subsequent work as I interpret it.

The idea that great earthquakes might effect the rotation of the earth was revived in the 1960's when measurements showed the extent of earthquake deformations. The idea has received continued interest since that time. These three decades of geophysics have also been noted for the development of the concepts of 'plate tectonics', in which it is recognized that the Earth is dynamic, and that earthquakes are an expression of relative motion between large surface blocks of the Earth.

In the paper above, Abraham notes coincidences of changes in the Earth's rotational energy and large earthquakes. His subsequent work was especially concerned with the further investigation and clarification of this matter. His thesis was that changes in the phase and amplitude of the Chandler nutation, motions of crustal mass, and earthquakes were all related to one another. His work, and the conclusions it led him to, took the following steps:

1. Taking Earth rotation data from Guinot (1972) Abraham tabulated second differences as a measure of change of phase and amplitude. The changes of phase, denoted $\Delta^2 T$, were described as 'shifts' of the rotation pole. The changes of amplitude, denoted $\Delta^2 R$, were described as 'jolts' of the rotation pole, and ascribed to impulsive motions.
2. The longitude λ of the Chandlerian rotation pole was calculated at the midpoint of each of Guinot's intervals of time, on the basis of Guinot's data.
3. Earthquakes with magnitudes $\geqq 7.9$ were tabulated from Duba (1965).
4. Signs for ν, the east-west motion of mass of Pacific Ocean plates causing a change in nutation, were derived for each interval from the signs of $\Delta^2 R$, $\Delta^2 T$ and λ.
5. The intervals associated with all $\geqq 7.9$ earthquakes in each seismic region were tabulated and entered with the $\Delta^2 T$ for each interval, its λ at that time, and the derived direction of motion ν. The entry in each interval was classified on the basis of the signs of λ and ν, so that four possibilities existed for the signs of λ and ν considered as a pair: $(++)$, $(+-)$, $(-+)$ and $(--)$.
6. Upon inspection of the data thus arranged, the sequences of abundances of ν in successive intervals near an earthquake were found to occur in two particular patterns. The seismically active regions of the Earth also fell into two categories:

   Region 1: Rynkysi, Peru-Andes, North America, Kasmir-China.

   Region 2: Aleutians, Japan, New Guinea-New Herbrides-Tonga, Indonesia-China.
7. The patterns found indicated that with respect to chronological time, the common sequence of events observed was an earthquake in Region 2, followed by a

shift $\Delta^2 T$, followed by an earthquake in Region 1, each in successive intervals.

Abraham recognised the wide implications that would follow from the establishment of such a pattern as described above. He noted the possibilities for a better understanding of when earthquakes would occur; of what causes the Chandler nutation to advance or retard; and of what maintains the nutation or causes its decay.

He would, I am sure, wish his notes and tables to be free for inspection by persons interested in these questions, and contact with the writer of this postscript is invited regarding them.

Invited Paper

Galactic Cosmic Ray Anisotropies in the Energy Range $10^{11} - 10^{14}$eV.

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Abstract: A review is presented of the evidence for anisotropies of galactic origin in the charged cosmic ray particle intensity at median primary energies of detection in the range $10^{11} - 10^{14}$eV. It concerns the period from 1958, when the first substantial long-term observations at energies of solar and sidereal modulation near 10^{11}eV commenced underground, until 1984, by which time results were available from a number of years of accurate observations with detectors of small air showers at energies near 10^{14}eV, too high for complicating effects of solar origin to be present. There is evidence for the existence of both unidirectional and bidirectional galactic anisotropies over the whole energy range. Tentative descriptive models are discussed in relation to advances both in solar and sidereal analytical techniques and in the ability of experimenters to account for and exploit the modulating influence of the heliomagnetosphere at the lower energies of detection.

Introduction

Although observations of anisotropies in the charged cosmic ray primary flux have extended up to energies around 10^{21}eV, this paper is confined to a review of experiments within a range of relatively low energies ($10^{11} - 10^{14}$eV) where the counting rates of the detecting systems are high and the evidence for galactic anisotropies now seems to be definite. It is not proposed to refer to the evidence in detail but rather to give some idea of the methods of analysis used and to show what the essential developments have been in the experimental field over the last twenty years or so.

Approximately 90% of the particle radiation consists of protons. Therefore it will be convenient to refer to it generally in terms of particle *energy* although it will be understood that particle *rigidity* must be used in many of the calculations to allow for application to the heavier component.

Because of the scattering of the particles out of their helical paths while propagating through magnetised space from the cosmic ray source regions to the Earth, over lifetimes of the order of 10^7 years, the radiation is characteristically highly isotropic and particle arrival times are statistically independent of each other. Clearly, there is no possibility of observing point sources of the radiation. What are observed are large-scale systematic spatial variations of small amplitude ($<0.1\%$) in the otherwise isotropic cosmic ray gas and changes in that anisotropic pattern with particle energy of detection and with time. The variations are observed in the counting rates, typically hourly, of fixed detecting systems — usually directional telescopes and, at the higher energies, air shower arrays — that rotate with the Earth. Because of the statistical uncertainties it is most desirable to achieve high counting rates. To this end, wide telescope apertures can be used, since the type of information is such that there is very little resulting loss of resolution. Again, since the index of the integral primary spectrum is negative, about -1.5, there are obvious statistical advantages in observing at the lowest practicable particle energies. Consequently, the bulk of experiments are carried out with wide angle telescopes near the low end of the energy range.

While information should certainly be obtainable about concentrations of cosmic ray sources, anisotropies otherwise tell us about the behaviour of the ionised and magnetised regions of space that are traversed by the particles en route from the sources. At the highest energies in the range galactic anisotropies should be directly observable. At the lower energies, distortion is caused by the heliomagnetosphere, because of its size, structure and time-varying behaviour. Moreover, superimposed anisotropies of heliospheric (solar) origin may be present. At these energies anisotropies can give important insights into heliomagnetic modulation, although the elucidation of galactic anisotropies becomes more difficult.

All told, investigations of galactic anisotropies should inform about such matters as the distribution of sources of the radiation, statistical acceleration processes for cosmic radiation in the galactic medium, bulk motions of the interstellar gas, the nature and degree of regularity of the galactic magnetic field (involving scale sizes of scattering centres) and about the heliomagnetosphere. It is the purpose here to review the progress that has been made in the detection and description of anisotropies that must precede identification with one or more of these galactic features.

Types of Anisotropies and Methods of Detection

Studies of galactic anisotropies have so far been concerned with two observed types, unidirectional and bidirectional. They may occur independently of each other or as components of a more complex total anisotropy. The unidirectional anisotropy shown as an example in Figure 1a is due to the motion of the solar system relative to a frame of reference in which the cosmic ray intensity can be regarded to be isotropic. A case in point would