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ORBITAL NOISE OF THE EARTH CAUSES INTENSITY FLUCTUATION IN THE GEOMAGNETIC FIELD

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Orbital noise of Earth's obliquity can provide an insight into the core of the Earth that causes intensity fluctuations in the geomagnetic field. Here we show that noise spectrum of the obliquity frequency have revealed a series of frequency periods centered at 250-, 100-, 50-, 41-, 30-, and 26-kyr which are almost identical with the observed spectral peaks from the composite curve of 33 records of relative paleointensity spanning the past 800 kyr (Sint–800 data) . A continuous record for the past two million years also reveals the presence of the major 100 kyr periodicity in obliquity noise and geomagnetic intensity fluctuations. These results of correlation suggest that obliquity noise may power the dynamo, located in the liquid outer core of the Earth, which generates the geomagnetic field.

Keywords: Orbital signal; frequency noise; geomagnetic intensity fluctuations; celestial mechanics; core-mantle system.

1. Introduction

The environment of the Earth is surrounded by a magnetic field which is believed to originate in the flow of the Earth's fluid core. Although specific heat sources in the Earth's core may produce convective motions which in turn drive the dynamo [1-7]; the dynamo process in the core which causes fluctuations of the geomagnetic intensity is a scientific mystery [8-14]. Recently, Guyodo and Valet [15] have integrated 33 records of relative paleointensity into a composite curve spanning the last 800 kyr (Sint-800), and Yamazaki and Oda [16] have obtained geomagnetic data for the past two million years. They have shown that the Earth's magnetic intensity fluctuated on a variety of time scales. The periods of their geomagnetic intensity fluctuations are almost identical with that of the frequency noise in the Earth's obliquity obtained by Liu [17-20]. This clear and strong correlation between the obliquity frequency noise and the geomagnetic intensity fluctuations suggests that the influence of the frequency noise in the orbital signals on the convection of the

Earth's liquid core may be the geodynamo that generates the planet's magnetic intensity fluctuations.

2. Influence of Orbital and Rotational Motion of the Earth on Geomagnetism

In order to understand the Earth's orbital and rotational motion as the cause of geomagnetism, it is necessary to introduce some fundamental notions of its gravitational interactions and torques. Gravitational interactions with the other planets (primarily Venus) may cause the orientation of the Earth's orbit to change with a dominant period near 70 kyr. Gravitational torques exerted by the Moon and Sun on the equatorial bulge of the Earth cause the rotational axis to precess with a period of about 26 kyr. If the orbital plane were fixed in space, the path of the rotational pole would be a circle centered on the orbital pole, keeping the obliquity fixed. However, neither the orbital nor the rotational axis is fixed in space. Because the orientation of the orbital plane is also precessing, the obliquity, ε, fluctuates by ±1 degree about its present value of 23.5 degrees with a period of 41 kyr. In addition, the frequency of the obliquity, ω_ε, also changes on a variety of time scales, with a dominant period near 100 kyr and other subsidiary oscillation periods [17-20]. Fig. 1 illustrates the aspects of the Earth's structure and average motions that are relevant to this study. The precession vector $\Omega = 7.7\text{x}10^{-12}$ rad/s is normal to the plane of the ecliptic. The Earth's angular rotation vector $\varpi = 7.3\text{x}10^{-5}$ rad/s is inclined relative to Ω. The angle between the Ω and ϖ vector (or the angle between the ecliptic and equatorial plane) is the obliquity ε as shown in Fig. 1. The red zone in Fig. 1 is the Earth's molten core, having a mean radius $R = 3.47\text{x}10^{8}$ cm. It should be noted that variations of the obliquity ε are defined as "orbital signals" because they are known and can be explicitly modeled. However, frequency variations in the obliquity ω_ε which are unknown are defined as "orbital noise" in the system [17-19].

The rotation of the Earth causes an equatorial bulge, resulting in a difference between the moments of inertia about the polar and equatorial axes. The ratio of this difference to the moment of inertia about the polar axis is known as the dynamic ellipticity. Because the density of the core is greater than the density of the mantle, the dynamic ellipticity of the core is much smaller than that of the mantle. The precession and obliquity rate of a planetary body are directly proportional to its dynamic ellipticity. If the core and the mantle are not coupled, the mantle could precess faster than the core precesses; thus the obliquity oscillations of the mantle and the core would not be in phase. Such an uncoupled motion in the mantle and core would lead to relative velocities on the core-mantle boundary.

The flow velocity V in the core, stirred by orbital forcing, can be expressed in terms of parameters ϖ, Ω, ω_ε and R. If the orbitally generated flow velocity V in the core is large enough to cause magnetoturbulent flow in the core, cycles with the obliquity frequency variation ω_ε should be observed in the magnetic field. Of the four orbital parameters for inducing flow velocity in the core, the parameter ω_ε is the only one whose influence on the geomagnetic field is not known. Note that the inclination is not an orbital parameter which induces flow velocity in the core.

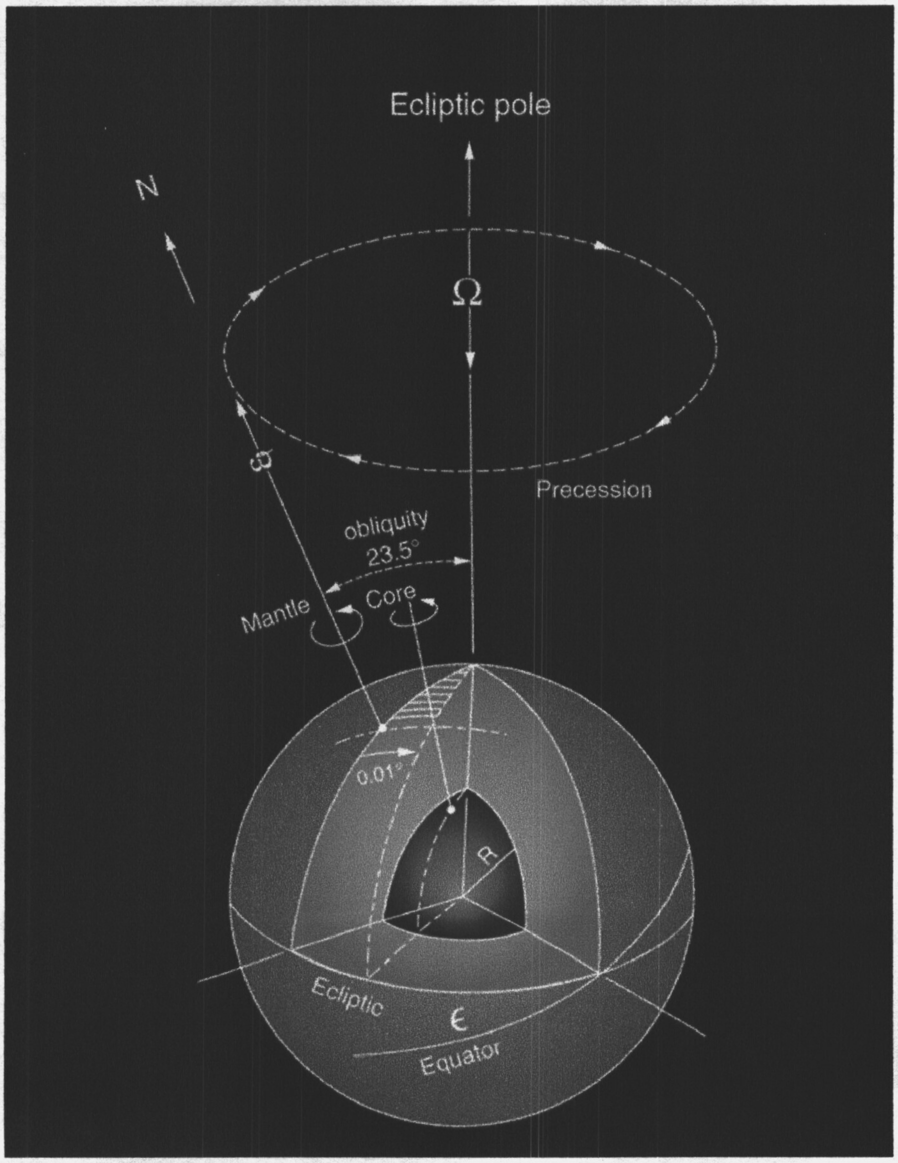

Fig.1. The Earth's obliquity and precession. Obliquity frequency modulation of the precession can stir flow velocity in the outer liquid core which is the geodynamo that generates the magnetic field of the Earth [9].

The geomagnetic field intensity is generally attributed to precession and obliquity. On the basis of the Pacific sediment data, it has been shown that geomagnetic field intensity may vary with the Earth's obliquity centered at 41 kyr, as a result of the obliquity effect on precession forces in the Earth's core [11]. Also, a spectral analysis of sedimentary record of relative geomagnetic paleointensity from two North Atlantic sites [12] shows significant power both at 100 kyr and 41 kyr, providing evidence for variation of the obliquity as an orbital forcing of geomagnetic field intensity.

3. Frequency Noise of the Obliquity

Frequency of the obliquity is a crucial orbital parameter associated with the regeneration of the geodynamo. Frequency noise in the obliquity is governed by [17-20]

$$\Delta\omega_{\varepsilon} = \frac{\mathrm{d}}{\mathrm{dt}}\left[\arctan\frac{\langle\Delta\varepsilon(t)\rangle}{\Delta\varepsilon(t)}\right] \quad (1)$$

in which

$$\langle\Delta\varepsilon(t)\rangle = \frac{1}{\pi}\int_{-\infty}^{\infty}\frac{\Delta\varepsilon(\tau)}{t-\tau}\mathrm{d}\tau \quad (2)$$

and

$$\Delta\varepsilon(t) = \sum_{i=1} A_i\cos(\gamma_i t + \zeta_i) \quad (3)$$

where amplitude A_i, frequency γ_i and phase angle ζ_i for i = 1, 2, 3......80 can be determined by secular evolution of the Earth's orbital and rotational motion [21].

The spectrum of the time series from Eq. (1) for the past 800 kyr is shown in Fig. 2a. The physical implications of this spectrum with regard to geomagnetic field intensity are: (a) a 250 kyr fluctuation could be preserved in geomagnetic record, (b) the split of the 100 kyr peak into two peaks at 120 kyr and 80 kyr is of particular interest to test the evolution of the geomagnetic field, and (c) peaks at 50-, 41-, 32-, and 26-kyr with relatively low intensity may also have an effect on the flow velocity in the Earth's core. The frequency spectrum for the obliquity is calculated using astronomical methodologies for the attraction of the Moon, planets and Sun on the equatorial bulge of the Earth. It does not include any possible third order effects, such as exchange of angular momentum between the Earth's mantle and core. These effects do exist, but they are trivial in the context here.

4. Geomagnetic Intensity Fluctuations

In the past decade, advances in paleomagnetic dating techniques have led to increasingly precise records of the relative intensity of the Earth's past magnetic field at numerous field sites. Compilation and analysis of these records can provide geomagnetic evidence for orbital signals. Guyodo and Valet [15] have presented the integration of 33 records of relative paleointensity [12, 22-26] into a composite curve spanning the past 800 kyr. In their composite Sint-800 curve, data conversion into virtual axial dipole moments (VADM) was done using volcanic records of absolute paleointensity. One characteristic of Sint-800 is that the intensity of the Earth's dipole field has experienced cyclic fluctuations with pronounced maxima and minima.

The spectrum of the Sint-800 record is shown in Fig. 2b, in comparison with the spectrum of the frequency variations of the Earth's obliquity. Fig. 2b shows that the power spectrum of VADM peaks at 250-, 100-, 50-, 41-, 30- and 26-kyr, which seem to mimic the frequency spectrum of the obliquity in Fig. 2a. We have calculated the correlation for the 800 kyr time interval overlap between the forms of the two power spectra in Fig. 2. The normal coherence coefficient, r, for this calculation was 0.89, which is very high. However, a high correlation between the two power spectra, although intriguing, is not a sufficient reason by itself to accept the hypothesis. To understand the periodicity evolution of the VADM, a wavelet analysis of the Sint-800 data is needed.

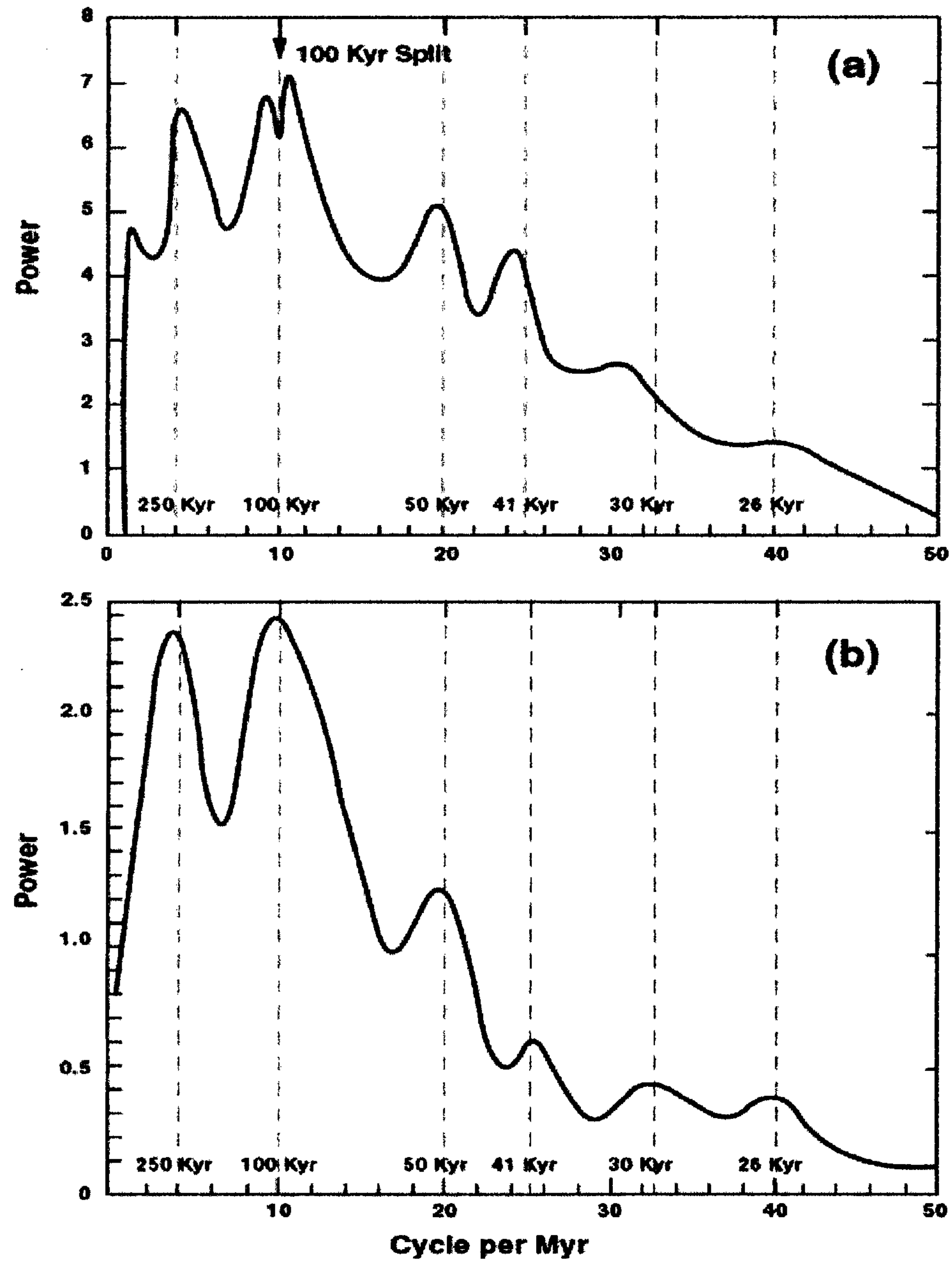

Fig.2. Power spectra: (a) Frequency spectrum of the Earth's obliquity over the past 800 kyr and (b) Virtual axial dipole moment (VADM) spectrum over the past 800 kyr (Sint-800) adapted from [15].

5. Wavelet spectrum of Sint-800

The time-frequency spectral behavior of the VADM time series can be demonstrated using Morlet wavelet transform which is a zero-mean, normalized, Gaussian-enveloped complex sinusoid [20]. The Morlet wavelet spectrum of the Sint-800 time series is illustrated in Fig. 3, in which the wavelet amplitude is displayed in the time frequency domain which peaks and troughs in horizontal successions in blue and green colors with red bars, indicating the presence of strong oscillations in the data. The background blue-green undulation indicates weak oscillations in question. In this way, the wavelet spectrum decomposes the time series Sint-800 into its time-frequency content.

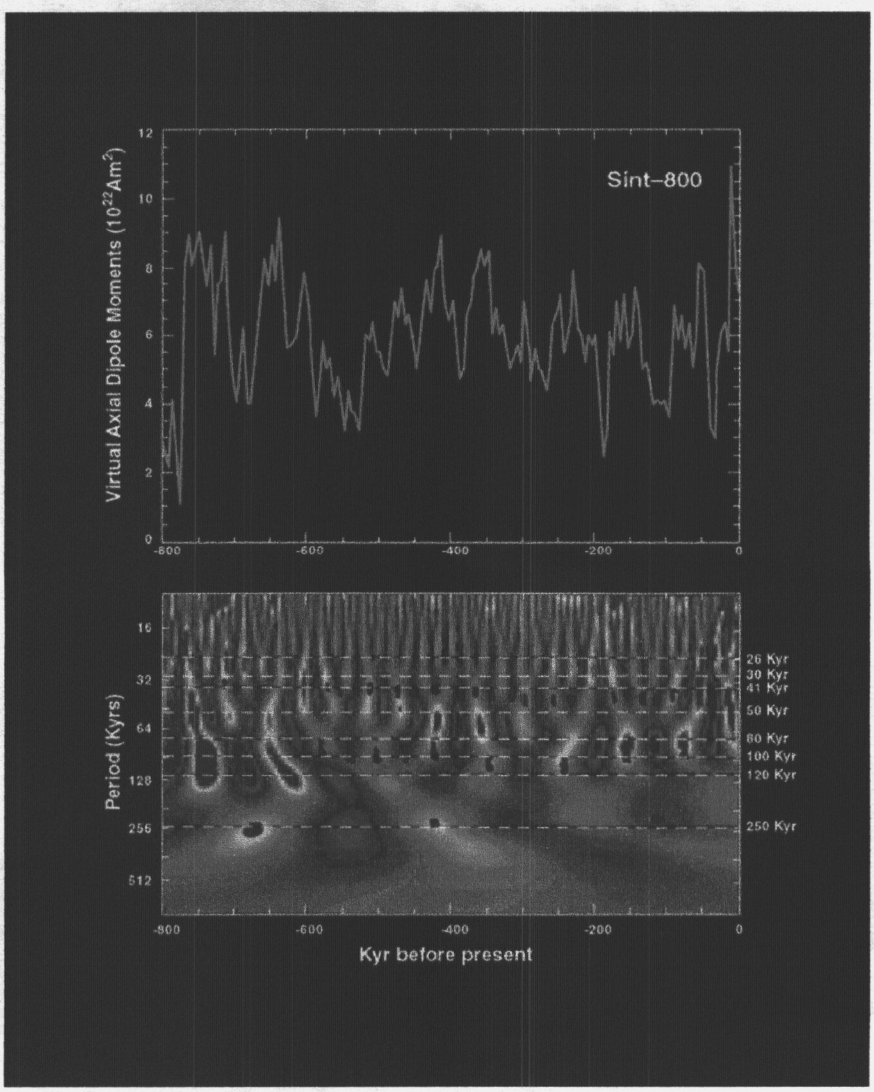

Fig. 3. Morlet wavelet spectrum [20] of the Sint-800 time series [15].

Spectral features in Fig. 3 demonstrate: (a) the 100 kyr VADM cycle seems to be a pseudoperiodic cycle varying in length from about 80- to 120-kyr, (b) the 41 kyr VADM cycle indicates a possible correlation with the 41 kyr obliquity frequency cycle [18], and (c) the periodic evolution of the VADM cycle at 250-, 50-, 30- and 26-kyr appears to be derived from the power peaks in the obliquity frequency spectrum shown in Fig. 2a. Therefore, the most important feature through which the orbital imprint may be unambiguously recognized in geomagnetic records is probably the obliquity modulation of the Earth's precession.

6. Frequency spectrum of the long-term obliquity variation

The correlation of the time series Sint-800 and obliquity frequency may be ambiguous because of the lack of continuous, long-term data with good age control. Long-term secular changes in the Earth's magnetic field are important for understanding the energy sources of the geodynamo, which produces the field [16]. Here we present a spectral analysis of the continuous frequency variations in the Earth's obliquity during the last 2250 kyr as shown in Fig. 4. The presence of the 100 kyr periodicity in Fig. 4 provides scientific explanation for the 100 kyr band in the power spectrum of relative paleointensity and magnetic susceptibility obtained by Yamazaki and Oda [16] from a marine sediment core 42 meters in length. It should be noted that this 100 kyr paleointensity band can also be seen in the time series of inclination [16], but it does not mean that one caused the other.

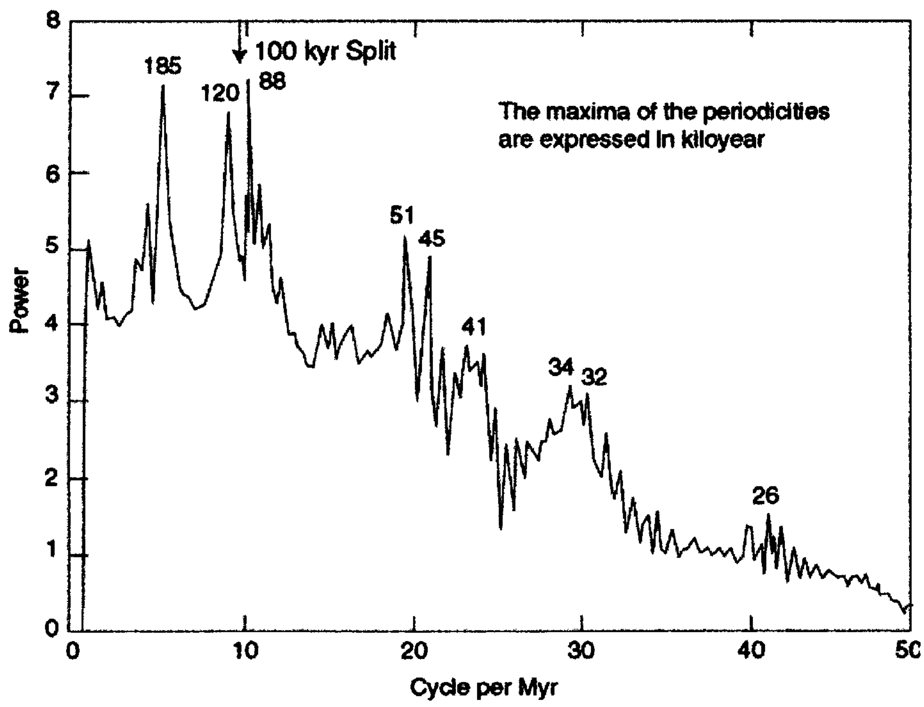

Fig. 4. Frequency spectrum of the Earth's obliquity over the past 2.25 million years. The split of the 100 kyr peak into two peaks indicates that the observed 100 kyr paleointensity fluctuation cycle may be irregular and unstable through time.

7. Discussion

Paleomagnetic measurements have shown that the geomagnetic field has always been dipolar and aligned with the axis of rotation. On shorter time scales, the dipole amplitude fluctuates around its mean values as shown in Fig. 3. This Sint-800 record [15] contains detailed information on the behavior of the geomagnetic field.

The geomagnetic dipole field is generated by a dynamo located in the liquid outer core of the Earth. Several groups of researchers have performed simulations of the complex hydromagnetic interactions in the core-mantle system involved in dynamo action [27-30]. These simulations are suggestive, but still far away from the correct parameter regime. For example, the ratio of viscous to Coriolis force is believed to be $E=10^{-15}$, but the simulations can handle only $E=10^{-6}$. It is therefore not clear to what extent they are representative of the geomagnetic field [31, 32]. Furthermore, model simulation data are not applicable to permit a meaningful spectrum comparison with the observations.

Because of this and because the simulations are extremely demanding in terms of computing resources, there is a need for generation mechanisms of the geomagnetic field that explain the dynamo process in terms of orbital signals. Unfortunately, orbital signals alone cannot decode the information contained in the observed geomagnetic fluctuation record. However, the frequency noise of the Earth's obliquity does permit a meaningful spectrum comparison with the observed Sint-800 data. While the geodynamo has widely been thought to be a self-sustained system, our results support the possibility of an external energy supply of the fluctuation through orbital noise.

We note that paleomagnetism is a well-developed field, and paleomagnetic analyses have been routine for decades. In practice, it is much easier to get reliable estimates of the direction of the paleomagnetic field in a sample than the intensity of the original external field causing the magnetism. The paleointensity can be estimated, but the uncertainties can be large [15]. In addition, even if the paleointensity is reliably estimated, there can be significant uncertainties in estimating the precise time at which the paleomagnetism was emplaced. Therefore our deductions, which are made from time series of paleointensity data, have ignored the noise in the data. The possible implications of the noise level in paleointensity data need to be investigated.

There is almost certainly significant convection in the outer core, involving considerable energy transfer. On the other hand, an external orbital effect could steer the form of the time variation of the geodynamo. The clear and strong correlation between the two spectra in Fig. 2 seems to suggest that the frequency noise of the obliquity may be the primary power source which injects sufficient energy into the core to power the dynamo and dominates over direct thermal effects.

8. Conclusion

Advances in celestial mechanics have led to precise results of the frequency variations in the Earth's obliquity. The noise effect of the obliquity frequency on the incoming solar radiation has already provided a physical mechanism that drives the major climate fluctuations for the past two million years [17-21, 33-35]. Results from the present study suggest that it is the frequency noise effect of the obliquity on the Earth's precession that causes intensity fluctuations in the geomagnetic field.

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POPULAR SUMMARY

The environment of the Earth is surrounded by a magnetic field which is believed to originate in the Earth's core. The conventional core theory holds that Earth has a heart of iron and nickel. An alternative hypothesis suggests a nuclear fission reactor at the core. While the geomagnetic field in the nuclear fission model is created by charged particles flowing around the fission reactor, the Earth's magnetic field in the conventional core model is generated by molten metal flowing around the solid inner core. Although specific heat sources in these two core models may drive the dynamo, the dynamo process in the core that causes fluctuation cycles of the geomagnetic intensity is a scientific mystery.

Recently, scientists have integrated 33 records of relative paleointensity of geomagnetic fields into a composite curve spanning the last 800 kyr (Sint –800) and obtained geomagnetic intensity data for the past two million years. They have discovered that the Earth's magnetic intensity fluctuated on a variety of cycles centered at 250-, 100-, 50-, 41-, 30-, and 26-kyr. What is the forcing mechanism which drives these geomagnetic intensity cycles ? In this paper, we attempt to answer this question scientifically.

Obliquity modulation of the Earth's precession can provide an insight into the core of the Earth that causes intensity fluctuations in the geomagnetic field. We show that the spectrum of the obliquity frequency have revealed a series of periods centered at 250-, 100-, 50-, 41-, 30-, and 26-kyr which are identical with the observed spectral peaks from the composite curves of Sint-800 data. This clear and strong correlation indicates that obliquity frequency modulation of the precession can stir flow velocity in the liquid outer core.

The results of our analysis have provided a rationale for understanding and integrating a wide range of observational data on space dynamics and geomagnetism. The conventional Earth's core models for geomagnetism should take the obliquity modulation effect on the precession into account because it is the driving mechanism of the geomagnetic intensity cycles.