data suggest that the noble gases are indeed of extraterrestrial origin and represent a mixture of solar and planetary components.

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Solar Cycle Signal in Earth Rotation: Nonstationary Behavior

Abstract. *Following the discovery of the 11-year solar cycle signal in earth rotation, linear techniques were employed to investigate the amplitude and phase of the difference between ephemeris time and universal time* (ΔT) *as a function of time. The amplitude is nonstationary. This difference was related to* $\Delta(LOD)$, *the difference between the length of day and its nominal value. The 11-year term in* $\Delta(LOD)$ *was 0.8 millisecond at the close of the 18th century and decreased below noise level from 1840 to 1860. From 1875 to 1925,* $\Delta(LOD)$ *was about 0.16 millisecond, and it decreased to about 0.08 millisecond by the 1950's. Except for anomalous behavior from 1797 to 1838,* ΔT *lags sunspot numbers by 3.0* $\pm$ *0.4 years. Since* ΔT *lags* $\Delta(LOD)$ *by 2.7 years, the result is that* $\Delta(LOD)$ *is approximately in phase with sunspot numbers.*

Currie (*1*) examined the time discrepancy between ephemeris time and universal time, $\Delta T = ET - UT$, from 1764 to 1978 compiled from four sources (*2*) and discovered the 11-year solar cycle signal in the record. Two-channel maximum entropy spectrum analysis (MESA) (*3, 4*) between ΔT and sunspot numbers, R_z (*5*), over different time spans suggested that the amplitude was nonstationary in time. In order to elucidate the time domain structure of the signal, a one-channel MESA of the entire ΔT record, linear prediction error smoothing, and band-pass filtering were employed. The analysis demonstrates that the signal is nonstationary and also shows that ΔT lags R_z, except for the interval 1797 to 1838. Since most salient results are presented in the time domain, an important side benefit of the analysis is that readers inexperienced in frequency-domain signal processing can visually assess the evidence.

A high-pass, zero phase shift filter with $2N + 1$ ($N = 10$) weights, whose frequency response is shown in Fig. 1a,

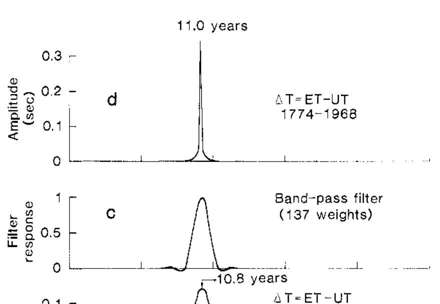

Fig. 1. (a) Frequency response of $2N + 1$ ($N = 10$) high-pass filter applied to ΔT and R_z series from 1764 to 1978. (b) Spectrum of high-pass filtered ΔT series. (c) Frequency response of $2N + 1$ ($N = 68$) band-pass filter applied to high-pass filtered extended ΔT series. (d) Spectrum of band-pass filtered ΔT series.

was convolved with the ΔT and R_z records. The response of the filter is unity for periods less than 15 years. The high-pass filtered series are plotted in Fig. 2, a and b. Fluctuations in ΔT are in the general range -2 to 2 seconds, and much of this power is ascribed (*6*) to hydromagnetic dynamo fluctuations in the earth's core (annual values of ΔT are given to an accuracy of 0.01 second).

Single-channel MESA (*7*) can be conceptually grasped by considering a common circumstance in the physical sciences. An observed input time series is passed through a "black box" that modifies the frequency and phase characteristics of the input to produce an output series. In the frequency domain the spectrum of the output series divided by that of the input equals the transfer function of the black box. In MESA the black box is termed a prediction error filter (PEF), and the filter is designed to reduce an arbitrary input series into an output random noise sequence whose spectrum is a constant. The spectrum of the input is thus proportional to a constant divided by the transfer function of the PEF.

In MESA the resolution of a sinusoidal signal is quite sensitive to the signal-to-noise ratio (SNR) and the length of the time series relative to the period of the sinusoid. As the SNR decreases the length (the order or the number of weights in the filter) of the PEF must be increased; as the record length decreases the PEF must also be increased (*8*). Single-channel MESA was applied to the ΔT series in Fig. 2a for increasing order of the PEF. The 11-year term became well resolved for a PEF of order 15, and the spectrum is depicted in Fig. 1b. For a longer PEF the peak bifurcates. Cohen and Lintz (*9*) suggested that the nominal 11-year term in the R_z record consists of several discrete frequency components. Such a model is not tenable for ΔT because objections (*10*) to a discrete multi-frequency Chandler wobble apply equally to the 11-year term in earth rotation (*11*).

The next task was to design a band-pass filter centered at 10.8 years whose shape approximated the ΔT spectrum. The response of such a filter with $2N + 1$ ($N = 68$) weights is shown in Fig. 1c. One cannot afford to convolve the filter with the ΔT series of Fig. 2a because this would entail loss of $2N = 136$ data points. Thus, the maximum entropy predictive filtering method (12) was employed, using a prediction filter of order 15, to generate 68 points off each end of ΔT. Convolving the band-pass filter with the extended ΔT series yields a record for 1774 to 1968 where power outside the passband has been eliminated. The spectrum of the band-pass filtered series is resolved for a PEF of order 3 and is shown in Fig. 1d. The mean amplitude for the entire record, obtained from one spectrum estimate at 11.0 years, is 0.34 second.

The band-pass filtered record is plotted in Fig. 3a. The only noise in the series is that within the passband, and it is not distinguishable from signal. The average amplitude for the whole record is 0.30 second, which agrees with the spectrum estimate. In order to estimate the noise as a function of time, band-pass filters centered at 7.4 and 14.8 years with $2N + 1$ ($N = 68$) weights were designed and applied to the extended ΔT series as before. Each band-pass filtered series is a pseudosine wave of approximate period 7.4 or 14.8 years, and the noise amplitude is estimated from the envelope of the maxima and minima. These estimates are shown as dotted curves in Fig. 3b. The upper dotted curve is from the 14.8-year pseudosine wave and, as one would expect, there is more noise at 14.8 than at 7.4 years. The solid line is the mean of the two dotted curves. The largest differences are from 1774 to about 1860, after which both noise estimates are near the mean. The mean noise estimates were subtracted from the absolute maxima and minima of the ΔT signal-plus-noise record to yield the envelope in Fig. 3c. The amplitude decreased from about 0.5 second in 1774 to below noise level by 1840. It began to increase near 1860 and remained between 0.10 to 0.14 second until about 1925. Thereafter it decreased to 0.04 second by the 1950's.

In carrying out the work encompassed in Figs. 1 to 3, I realized that the band-pass filter is highly tuned and some distortion is inherent in the ΔT series of Fig. 3a. Therefore, broader band-pass filters for $2N + 1$ ($N = 20$, 30, and 40) weights were designed and applied as before. Broadening the passband increases the noise and thus amplitudes increase as N decreases. However, in all three instances the salient features of Fig. 3a were reproduced; to illustrate this, results for $N = 30$ are presented in Fig. 4a.

Analyses of ΔT in Figs. 1, 3, and 4 were repeated for sunspot numbers where the spectrum of the R_z series in Fig. 2b was resolved for PEF of order 7. Results for $N = 20$ are presented in Fig. 4b. In both panels of Fig. 4 the tick mark for each positive maximum is an average, to 0.1 year, for the four analyses of each record. The solid dots in Fig. 4b denote the year and amplitude of R_z maxima and minima in Fig. 2b. The band-pass filter has smoothed extremal maxima and minima of R_z, but the well-known minimum in the early 19th century is reproduced as well as the larger and broader minimum centered near 1900. These results independently support the reality of the nonstationary features found in ΔT.

From 1857 to 1946, from mean years of maxima and minima, ΔT lags R_z by 3.0 ± 0.4 years, as can be adduced from Fig. 4. The time lag is about zero by 1957, but whether this is a real phenomenon or is due to an "end effect" of the band-pass filter or the very weak signal in ΔT is not certain. In the interval centered about 1840 to 1850 the signal is below noise level. Beginning with the ΔT maximum at 1775.8, ΔT lags R_z by a mean 3.1 years; in 1797.2 the lag increases to about 4.8 years; in 1802 to 7.4 years; and in 1807 to 8.3 years. It then settles between 9 and 10 years from 1813 to 1828. Cycle skipping seems an unlikely explanation, so I am inclined to view this perplexing phase behavior as a real effect.

Gross estimates (1) for the amplitude of ΔT were 0.6 second for 1774 to 1850, 0.1 second for 1838 to 1969, 0.2 second for 1838 to 1903, and 0.04 second for 1904 to 1969. Corresponding estimates from Fig. 3c obtained by using linear techniques and recasting results into the

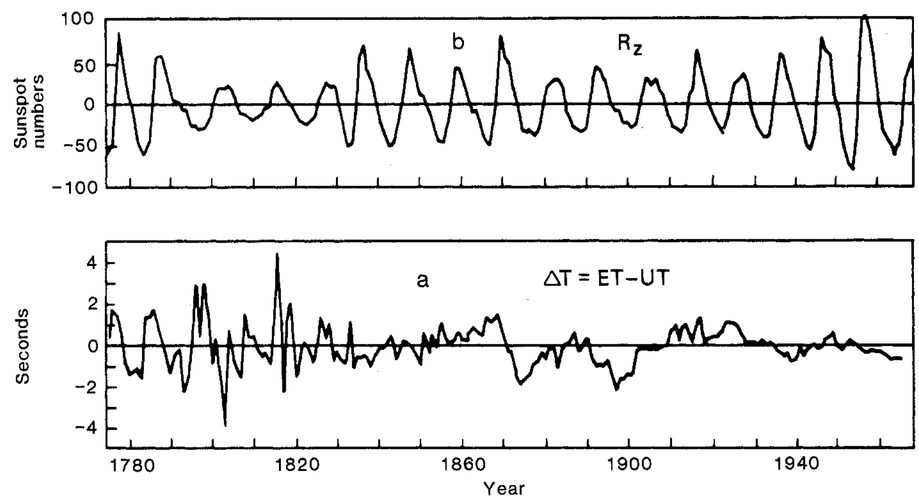

Fig. 2. High-pass filtered ΔT and R_z series from 1774 to 1968. The frequency response of the $2N + 1$ ($N = 10$) high-pass filter applied is depicted in Fig. 1a.

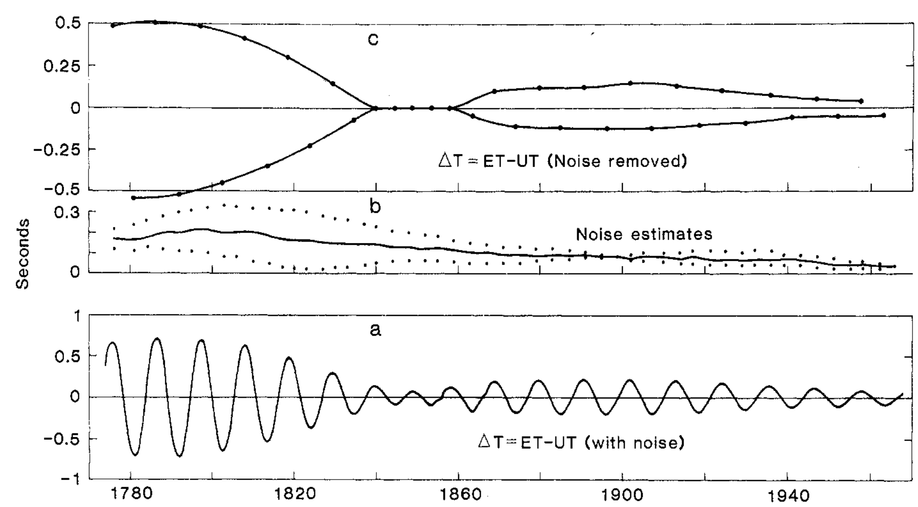

Fig. 3. (a) Plot of $2N + 1$ ($N = 68$) band-pass filtered ΔT series. (b) Dotted curves are noise estimates at 7.4 and 14.8 years; solid curve is the mean of the two dotted curves. (c) Envelope of band-pass filtered ΔT series after noise is removed.

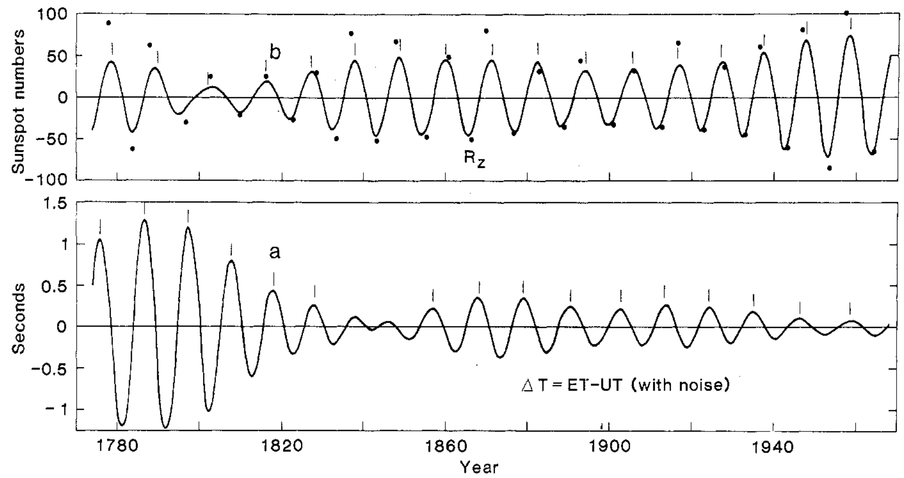

Fig. 4. (a) Plot of $2N + 1$ ($N = 30$) band-pass filtered ΔT series. (b) Plot of $2N + 1$ ($N = 20$) band-pass filtered sunspot numbers (see text).

time domain are 0.3, 0.09, 0.11, and 0.08 second. The linear analysis confirms the suggestion (*1*) that the signal was anomalously large in the late 18th and early 19th centuries. As regards phase, we can adduce from the tick marks in Fig. 4 that ΔT lags R_z by 3.0 ± 0.4 years from 1857 to 1946. This is in good agreement with the estimate given by Currie (*1*) based on two-channel MESA. However, the report that the same time lag held from 1774 to 1850 is spurious. Figure 4 shows such a lag from 1775.8 through 1792, but thereafter the phase radically changed. Reexamination of the computer listings on which the earlier paper was based disclosed that the phase had a strong linear trend whose mean lag of 3.4 years was fortuitous. A final interesting feature of Fig. 4 is that there is no apparent relation between the R_z and ΔT amplitudes.

The measured astronomical record is ΔT, but physically the significant quantity is Δ(LOD), the difference between the length of day and its nominal value. A. Arking and M. G. Rochester have provided a derivation of the relation from first principles: $\Delta T = ET - UT = (\omega L_0/2\pi - 1)t$, where ω is the angular velocity of earth rotation in radians per second and L_0 is 8.64×10^4 seconds in a day. Taking the time derivative of ΔT and relating it to the LOD, we have LOD $= 2\pi/\omega \simeq L_0[1 - d(\Delta T)/dt]$, and thus $\Delta(\mathrm{LOD}) = \mathrm{LOD} - L_0 = -L_0\, d(\Delta T)/dt$. Let the 11-year term be represented by $\Delta T = c_0 \cos(2\pi t/\tau)$ seconds, where c_0 is constant only over subsets of the record and $\tau = 11(365.25)L_0$ seconds. We then obtain

$$\Delta(\mathrm{LOD}) = \frac{c_0 2\pi}{11 \times 365.25} \sin\left(\frac{2\pi t}{\tau}\right) \text{ seconds} \quad (1)$$

The constant c_0 can be ascertained from Fig. 3c and related to Δ(LOD) by Eq. 1. The result is that Δ(LOD) was 0.8 msec in the late 18th century and rapidly decreased to below noise level by 1840. Its amplitude began to increase about 1860 and remained near 0.16 msec until 1925. Thereafter it gradually decreased to at least 0.08 msec by the 1950's. Thus $\Delta(\mathrm{LOD})/L_0$ has varied from 1×10^{-9} to 2×10^{-9} since 1860, but at the close of the 18th century it was an order of magnitude larger at 10^{-8}. The annual term in Δ(LOD) in the 20th century is 0.5 msec (*11*). Arking observed that ΔT lags Δ(LOD) by 90° or (90/360)11 = 2.7 years. Since ΔT lags R_z by 3.0 ± 0.4 years from 1857 to 1946, the result is that Δ(LOD) and R_z are approximately in phase over this time span.

I have implicitly adopted the view (*11*) that all the variance in Δ(LOD) is due to fluctuations in earth rotation. For lack of a plausible alternative, I conclude that the ultimate source of energy for the 11-year term must originate on the sun. There are two possible transfer functions: the solar wind, or an 11-year variation in the solar constant. The annual term in Δ(LOD) is a proxy index of climate change at that period and it is difficult to reach any other conclusion vis-à-vis the 11-year term.

The evidence for a solar cycle signal in height of sea level (*13*) and in surface air temperature (*14*) is good, but it is for one region of the oceans and one continent. Only along the coastal regions of northern Europe are there numerous records of sea level extending back into the 19th century. In contrast, a solar cycle signal in Δ(LOD) is a modulation of the angular momentum of the entire mantle and core of the earth, and the evidence for the signal in the frequency domain (Fig. 1) and time domain (Figs 3 and 4) is quite good.

If one accepts the evidence for an 11-year term in Δ(LOD), the most important result may be that the signal in the late 18th and early 19th centures was five to ten times larger than it has been since about 1860. I am also inclined to view the anomalous phase behavior during this interval as real. The forcing or excitation function for the signal is not known, although I suggest that the winds responsible for the annual term (*11*) generate the 11-year term as well. There is a consensus (*15*) that the Little Ice Age nominally began in 1430 and ended in 1850. It is therefore intriguing that the unusual behavior of Δ(LOD) from 1774 to 1850 coincided with the close of the Little Ice Age. This may be coincidence; it may also be consequence. Lamb (*16*) indicated that during such a climate excursion the zonal westerly circumpolar vortex winds become stronger and shift equatorward. Evidence for a solar cycle signal in these winds has recently been found (*17*).

Since about 1925 the Δ(LOD) amplitude has decreased. In the 1950's it reached a value smaller by a factor of 6 than the 0.5-msec annual term. It is not certain the signal is above noise level at this time. Elucidation of the forcing function for the annual term was successful because of its relatively large amplitude and because investigators knew the two optimal times of year (January and July) to carry out the computations (*11*). If the forcing function is in phase with Δ(LOD), the optimal epochs for detecting an 11-year term in zonal wind data are at the successive maxima and minima in Figs. 3a and 4a advanced forward in time by 2.7 years. For the years since adequate data became available, these epochs are 1932.4, 1937.8, 1943.3, 1949.0, 1955.2, 1961.1, and 1967.0. The dates of the last three epochs are uncertain. If the 11-year term in Δ(LOD) reaches magnitudes recorded at the close of the Little Ice Age, the task will be easy.

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Scheiner's Halo: Evidence for Ice Ic in the Atmosphere

Abstract. *Refraction of sunlight at the angle of minimum deviation between octahedral faces of crystals of ice Ic in the upper atmosphere could produce a halo around the sun or the moon at 27.46°. Crystals of hexagonal ice having low-index faces cannot produce a halo of this radius. It is therefore suggested that Scheiner's halo, which has been reported at least four times since 1629 at 28° from the sun, is due to ice Ic. If this is correct, it is apparently the first evidence that ice Ic occurs naturally and that liquid water can freeze to ice Ic.*

Scheiner's halo is a rare halo that occurs at ~ 28° from the sun or the moon. It was first reported by Scheiner more than 350 years ago (*1*) and has been confirmed several times since (*2–4*), but no convincing explanation has been proposed. Seven other halos have been reported (*5*). They are caused by light passing at the angles of minimum deviation through crystals of ordinary hexagonal ice, ice Ih, that have faces whose Miller indices are either 0 or 1. The purpose of this report is to suggest that Scheiner's halo is caused by light passing at the angle of minimum deviation through octahedral crystals of cubic ice, ice Ic.

In both ice Ih and ice Ic, each water molecule is hydrogen-bonded to four neighbors in a nearly perfect tetrahedral arrangement, and the tetrahedra are stacked differently to give the hexagonal and cubic structures, which have the same density. Several reviews (*6–9*) of their properties have been published. Ice Ih is the only form of ice that is known to occur naturally on the earth. Ice Ic is always metastable relative to ice Ih and can therefore only be made from a less stable phase of water than Ih. It seems that below ~ 180 K, all phases transform to it rather than to Ih. For example, when the vapor condenses on a substrate below ~ 180 K, ice Ic is formed if the temperature is not too low, and otherwise amorphous ice is formed. Amorphous ice and all the high-pressure phases that can be recovered in a metastable form at low temperature and pressure (*10, 11*) transform first to ice Ic on heating. Ice Ic is therefore kinetically preferred over ice Ih in transformations from a less stable phase below ~ 180 K, although Ih is the thermodynamically preferred form. Near the melting point, ice Ih is always formed. At intermediate temperatures there must therefore be intermediate probabilities of forming ice Ic.

Ice Ic has never been made from the liquid. However, the liquid can be cooled to ~ 230 K if heterogeneous nuclei are not present, and it is possible that at least sometimes the drops freeze to form ice Ic. Many droplets of water exist in the upper atmosphere at temperatures down to ~ 230 K (*12*), and naturally formed ice Ic may occur there. The question arises how to detect it if it does.

One way is by means of halos. At least eight halos occur around the sun or the moon (*5, 13–16*), of which seven are due to hexagonal ice. Scheiner's halo, however, cannot be explained by refraction by crystals of ice Ih having low-index faces. It could be explained by invoking crystals having higher index faces, but then, as Tricker (*17*) pointed out, many other halos ought to have been observed but have not been. Tricker (*17*) suggested that it is an upper arc caused by light refracted through the (10.0) and (10.1) faces (m_1p_1 in the usual halo nomenclature) of a doubly oriented crystal of ice Ih. The arc should be about 33° and 24° above the sun when the sun is at 0° and 10° elevation, respectively. If this is so, then the halo should be seen only when the sun is somewhat less than 10° above the horizon and should occur above the sun. However, the halo was observed by Whiston (*2*) at London at about 10:15 a.m. on 1 March 1727 as a short arc that appeared briefly at about 50° from the vertical, and by Greshow (*3*) at Paris at 8:40 p.m. on 20 October 1747 as a left lateral arc of the moon and at 9:32 p.m. as a right lateral arc. C. G. Andrus and H. L. Riley observed the halo at Sand Key, Florida, at 3:00 p.m. on 11 May 1915 at about 315° from the vertical (*4*). These three observations are inconsistent with Tricker's explanation. Besson (*18*) reported observing at Paris at 5:38 p.m. on 26 March 1906 a spot 28° above the sun when the sun was 6° above the horizon. It is usually identified (*19*) with Scheiner's halo, but it appears to agree approximately with Tricker's prediction and so may not be Scheiner's halo.

Andrus and Riley also reported observing simultaneously parts of the 22°, 18.5°, 17.5°, and 8.5° halos, and Andrus sketched their appearance (*4*). All but the 28° halo were approximately symmetric about a common diameter, but the 28° halo was well off the diameter and did not cut it. This is consistent with independent origins for the 28° and the other halos.

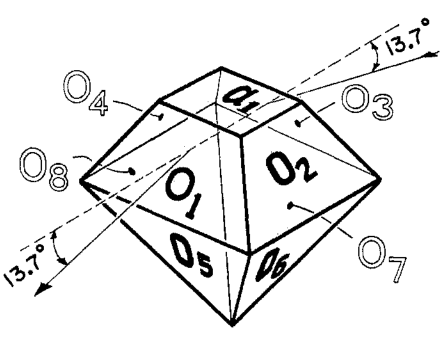

Fig. 1. Octahedron with one corner truncated to show the o_1o_3, . . . faces that cause Scheiner's halo and the a_1o_5, . . . faces that cause a halo at 19.7°.

Observable single crystals of ice Ic have never been made, and so its crystalline form is unknown. If it formed cubic crystals and its refractive index were the mean refractive index of ice Ih, it would cause a halo at 46°, which coincides with the halo caused by refraction through the side and end faces of a hexagonal column of ice Ih. If it formed octahedral crystals, however, as illustrated in Fig. 1, only the (111) and $(\bar{1}\bar{1}\bar{1})$ faces, which are labeled o_1 and o_3, respectively, and the 11 related pairs of faces would form prisms having an angle of minimum deviation. The prism angle is 70.528° by symmetry,