Origin of the Glacial Cycles: A Collection of Articles

Glacial Cycles and Orbital Inclination

Richard A. Muller and Gordon J. MacDonald
Letter reprinted from *Nature*, Vol. 377, No. 6545, 14 September 1995, pp. 107–108.

Glacial Cycles and Astronomical Forcing

Richard A. Muller and Gordon J. MacDonald
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Spectrum of 100-kyr Glacial Cycle:
Orbital Inclination, not Eccentricity

Richard A. Muller and Gordon J. MacDonald
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Simultaneous Presence of Orbital Inclination and Eccentricity in
Proxy Climate Records from Ocean Drilling Program Site 806

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Simultaneous Presence of Orbital Inclination and Eccentricity in
Proxy Climate Records from Ocean Drilling Program Site 806:
Comment and Reply

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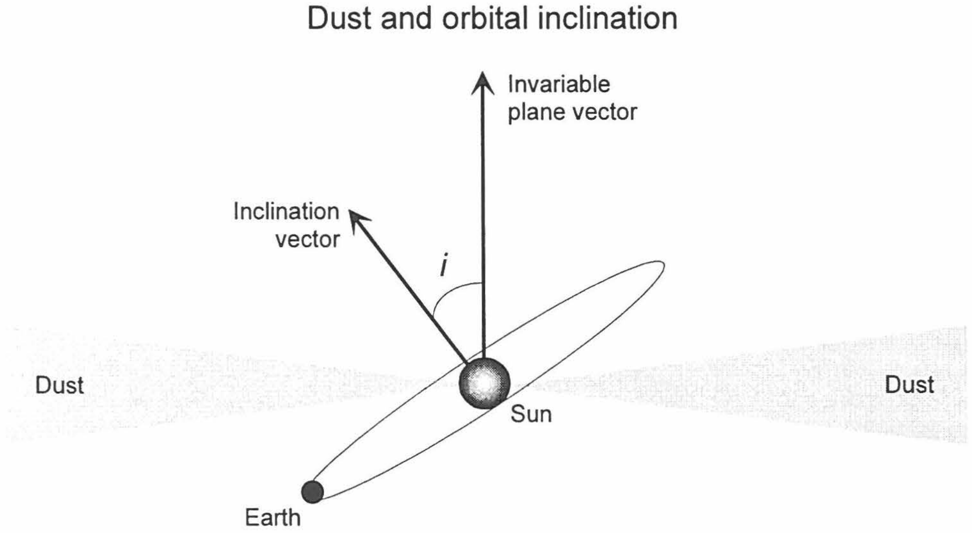
Introduction

This collection of articles describes a new theory of glacial cycles and its application to a number of data sets that represent conditions during glacial times. The widely held conventional theory of glacial cycles, which is due to Milankovitch, attributes cycles in the earth's ice cover to perturbations in the motion of the earth and the resulting changes of insolation (solar heating) in the Northern Hemisphere. The strongest effects are expected to come from changes in the earth's *obliquity* (tilt of the earth's spin axis with respect to its orbit) and from the *precession* term that accounts for the delay between summer solstice (when the pole faces the sun) and perihelion (when the earth is closest to the sun). Perturbations of the earth's motion come from gravitational effects of the planets and the moon, and can be calculated with precision back at least 10 million years.

The insolation mechanism of Milankovitch has difficulty accounting for the relative magnitudes of the cycles. The spectrum for the last 900 kyr is dominated by the 100-kyr period attributed in the Milankovitch theory to oscillations of the eccentricity e. But yearly average insolation is proportional to $(1/2)e^2$ and the calculated 4% variations in e yield insolation changes of only 10^{-3}. Calculations show that the solar insolation at a typical latitude (60°N) at the primary frequencies for (precession, obliquity, eccentricity) to be in the ratio (1, 0.2, 0.02), in sharp disagreement with data on climate proxies. The observations indicated that the eccentricity variation, rather than being 50 times smaller than precession, is 11 times larger. Further difficulty with the conventional theory is that the eccentricity shows a 400-kyr cycle that is much stronger than the 100-kyr variation. The 400-kyr period is absent in data sets of climate proxies.

Another parameter describing the motion of the earth is the inclination i of the earth's orbital plane with respect to the invariable plane of the planetary systems. The invariable plane of the solar system is a plane perpendicular to the total angular momentum vector of the planets, as illustrated in the figure below. Over the past million years, the inclination has varied from about half a degree to about 3 degrees. During the time of low inclination, the earth accretes interplanetary dust at a greater rate than at times of high inclination. The dust particles, under the gravitational pull of the perturbing planets, tend to be concentrated in the invariable plane.



Dust particles can affect climate by altering the amount of solar radiation reaching the lower part of the atmosphere. At the high altitudes where the dust particles enter the atmosphere, the particles themselves can attenuate the incoming solar radiation, can sweep up water vapor which is a warming greenhouse gas and can nucleate water particles to form high-altitude (noctilucent) clouds. The clouds would themselves reflect radiation.

While the detailed mechanisms of how astronomical dust can influence climate have not been completely worked out, this collection of articles shows that variation in inclination provides a better match for data sets on climate proxies than do variations of eccentricity. The theory also requires that density of dust in the vicinity of the variable plane vary with time. Beginning about a million years ago, the 100-kyr cycle became the dominating feature of variations in the total volume of ice covering the earth. Before that time, weaker variations are seen with 40-kyr and 20-kyr periods, consistent with variations in obliquity and precession.

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Glacial Cycles and Orbital Inclination

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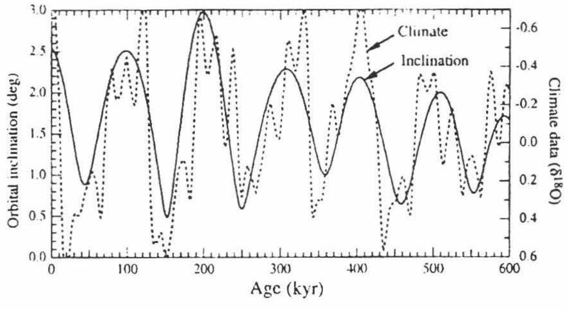
Glacial cycles and orbital inclination



Comparison of orbital inclination (solid line, lagged by 33 kyr) and $\delta^{18}O$ climate data (dotted line) from SPECMAP[5].

SIR — According to the Milankovitch theory, the 100-kyr glacial cycle is caused by changes in insolation (solar heating) brought about by variations in the eccentricity of the Earth's orbit. There are serious difficulties with this theory: the insolation variations appear to be too small to drive the cycles, and a strong 400-kyr modulation predicted by the theory is not present. Moreover, the amplitude of the glacial cycle has been large at times (400 years ago and today) when the eccentricity modulation has been near zero; this conflict is also called the 'Stage-11 problem'[1]. In addition, improved measurements have uncovered an apparent causality problem: the sudden terminations of the glacial cycles appear to precede the increases in insolation[2,3], although this interpretation has been disputed[4]. We suggest that a radical solution is necessary to solve these problems, and we propose that the 100-kyr glacial cycle is caused, not by eccentricity, but by a previously ignored parameter: the orbital inclination, *i*, the tilt of the Earth's orbital plane.

Ancient climate is recorded in sediment through change in the oxygen isotope ratio, $\delta^{18}O$, which is believed to reflect the percentage of the Earth's water frozen in ice. The figure shows $\delta^{18}O$ (dotted line) for the past 600,000 years from the SPECMAP compilation of data from five sea-floor sediment cores[5]. The figure also shows the orbital inclination (solid line), calculated by direct integration of planetary perturbations[6], transformed to the invariable plane (the plane of symmetry of the Solar System), and shifted to give the best least-squares fit to the $\delta^{18}O$ data. (Only three parameters were adjusted, one for the delay and two for the overall scale.) For the best fit, *i* preceded $\delta^{18}O$ by 33±3 kyr; as this is positive, there is no causality problem. Similarly, the presence of a strong variation in *i* near 400 kyr solves the Stage-11 problem.

The existence of the 100-kyr cycle of orbital inclination does not seem to have been noticed previously by climatologists or astronomers. It may have been missed for two reasons. Ever since Milankovitch, the implicit assumption has been that insolation is the driving force for climate cycles, and insolation is not directly affected by orbital inclination. Second, the 100-kyr cycle is not evident when *i* is calculated in the usual reference frame based on the present orbit of the Earth. Only when transformed to the invariable plane (or a plane near it) does the 100-kyr cycle unmix from the obscuring effect of a strong 70-kyr orbital precession cycle. We note that a 70-kyr cycle has been reported in $\delta^{18}O$ data from other sedimentary samples[7], and we suggest that this cycle may be related to orbital precession.

The only mechanism we have found that could link orbital inclination to climate is extraterrestrial accretion of meteoroids or dust. Such material can be detected in ice and sedimentary rock by analysis of iridium; Walter Alvarez has pointed out that extraterrestrial dust cycles could be detected using ^{3}He. If this mechanism is correct, a 100-kyr cycle should be seen in ice and sediment records of extraterrestrial accretion.

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1. Imbrie, J. *et al. Paleoceanography* **8**, 699–735 (1993).
2. Broesker, W. S. *Nature* **359**, 596 (1993).
3. Landwehr, J. *et al. Science* **368**, 594 (1994).
4. Imbrie, J. *et al. Nature* **363**, 531–533 (1993).
5. Imbrie, J. J. *et al.* in *Milankovitch and Climate* Pt 1 (eds Berger, A. L. *et al.*) 269–305 (Reidel, Dordrecht, 1984).
6. Quinn, T. R., Tremaine, S. & Duncan, M. *Astr. J.* **101**, 2287–2305 (1991).
7. Ruddiman, W., Raymo, M., Martinson, D., Clement, B. & Blackman, J. *Paleoceanography* **4**, 353–412 (1989).

Glacial Cycles and Astronomical Forcing

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Glacial Cycles and Astronomical Forcing

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Narrow spectral features in ocean sediment records offer strong evidence that the cycles of glaciation were driven by astronomical forces. Two million years ago, the cycles match the 41,000-year period of Earth's obliquity. This supports the Croll/Milankovitch theory, which attributes the cycles to variations in insolation. But for the past million years, the spectrum is dominated by a single 100,000-year feature and is a poor match to the predictions of insolation models. The spectrum can be accounted for by a theory that derives the cycles of glaciation from variations in the inclination of Earth's orbital plane.

Nearly as soon as the ice ages were discovered, their origin was attributed to astronomical causes. In the late 1800s, James Croll assumed that the ice ages were driven by changes in insolation (solar heating) brought about by variations in Earth's orbit and spin axis (*1*, *2*). According to Croll, and to Milankovitch after him (*3*, *4*), the main orbital parameters that affect insolation and its distribution are Earth's orbital eccentricity, obliquity (the tilt of Earth's poles toward the sun), and precession (the lag between equinox and perihelion). However, it was not until 1970 that Broecker and van Donk (*5*) established that glaciation in the late Pleistocene was truly periodic and was dominated by a 100,000-year (100-ky) cycle. This period was soon identified with the quasiperiodic 100-ky cycle of Earth's eccentricity. (We will offer evidence that this identification was premature.) In addition, another strong cycle was discovered with a 41-ky period that matched the cycle of changes in Earth's obliquity (*6*). This 41-ky cycle appears to have dominated glacial changes from 1.5 to 2.5 million years ago (Ma) (*7*). The 100-ky cycle has dominated from 1 Ma to the present.

Much of the best data for paleoclimate studies comes from ocean sediments, in which proxies for climate, preserved in fossils, are measured as a function of depth. The oxygen isotope ratio $\delta^{18}O$ is believed to reflect the amount of Earth's water frozen in ice and thus is a measure of Earth's global ice volume. To turn a record of $\delta^{18}O$ versus depth into a record versus time, the sedimentation rate must be estimated. This is often done with a process called tuning, in which the instantaneous sedimentation rate is deduced by matching cycles in $\delta^{18}O$ to calculated perturbations in Earth's orbit. Parameterized sedimentation rates are adjusted to bring the observed proxy variations into consonance with the predictions of the model. This approach is potentially circular if the results are used to validate the climate model used to tune the record. Neeman (*8*) has demonstrated with Monte Carlo tests that, given enough parameters, tuning procedures can successfully match data to an incorrect model, resulting in an inaccurate time scale as well as in a false validation of the model. Therefore, for the present work, we emphasize the use of time scales that are untuned and assume constant sedimentation with average rates constrained by radiometrically measured control points.

A strong case for astronomical forcing of glacial cycles comes from analysis of $\delta^{18}O$ data for the age interval 1.5 to 2.5 Ma from Deep Sea Drilling Project (DSDP) site 607, located on the west flank of the Mid-Atlantic Ridge. For a full description of the stratigraphy, dating, and magnetic correlation, see Ruddiman *et al.*

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(7) and Raymo *et al.* (9). In their spectral analysis of the $\delta^{18}O$ data for the time interval 1.60 to 2.75 Ma, Ruddiman *et al.* (10) found a 41-ky peak with a full width at half maximum (FWHM) $\Delta f/f$ of 12%. This is close to the width that would be obtained for a pure sine wave, using the low-resolution spectral method that was employed [Blackman-Tukey (11) with 1/3 lags (12)]. However, the time scale of this record had been tuned to obliquity, so it was conceivable that the relatively narrow width was an artifact of tuning.

The $\delta^{18}O$ data versus depth are shown in Fig. 1A. To make an analysis that does not depend on tuning, we calculated the spectral power as a function of cycles per meter, using a method (13) that has about three times better frequency resolution than the method used by Ruddiman *et al.* The resulting spectrum is shown in Fig. 1B. It has one strong peak near 0.52 cycles/m, with statistical significance greater than 99.9% (14). To place a time scale on the data, we assumed the same average sedimentation rate (15) used by Raymo *et al.* for this interval: 45.6 m per million years. With this sedimentation rate, the peak in Fig. 1B appears near the 41-ky period of obliquity.

The narrow width of this peak is the salient feature for the present discussion. The peak has a FWHM of $\Delta f/f$ = 3.7%. This is the same width that we obtain when we perform the same analysis on a pure 41-ky sine wave (or on any other perfectly periodic function, such as triangular, whose fundamental component is at 41 ky) for the same 1-million-year duration (16). The fractional width of a periodic signal is independent of the assumed sedimentation rate but depends solely on the number of cycles in the interval (17). The presence of a narrow peak in untuned data requires two phenomena: the existence of a nearly constant sedimentation rate and the presence of a truly periodic signal.

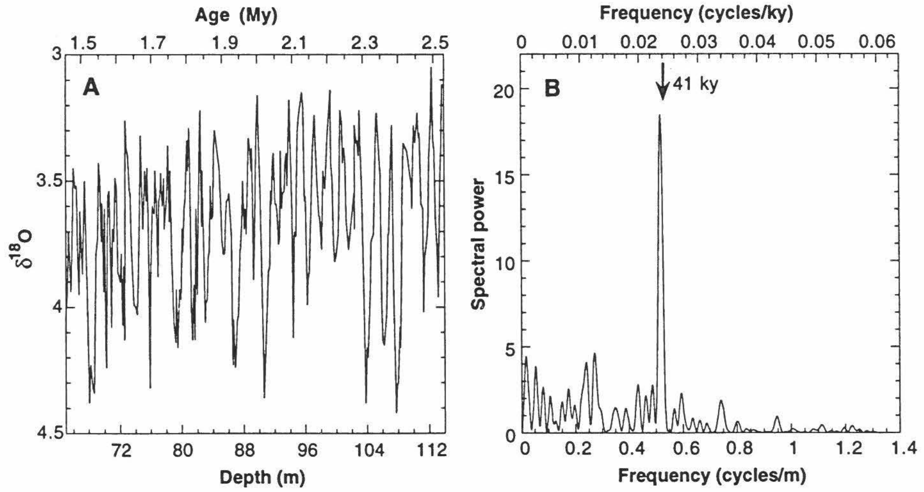

Fig. 1. (**A**) $\delta^{18}O$ data in parts per thousand and (**B**) spectral power for DSDP site 607, for the interval from 1.5 to 2.5 Ma. The time scale assumes a constant sedimentation rate.

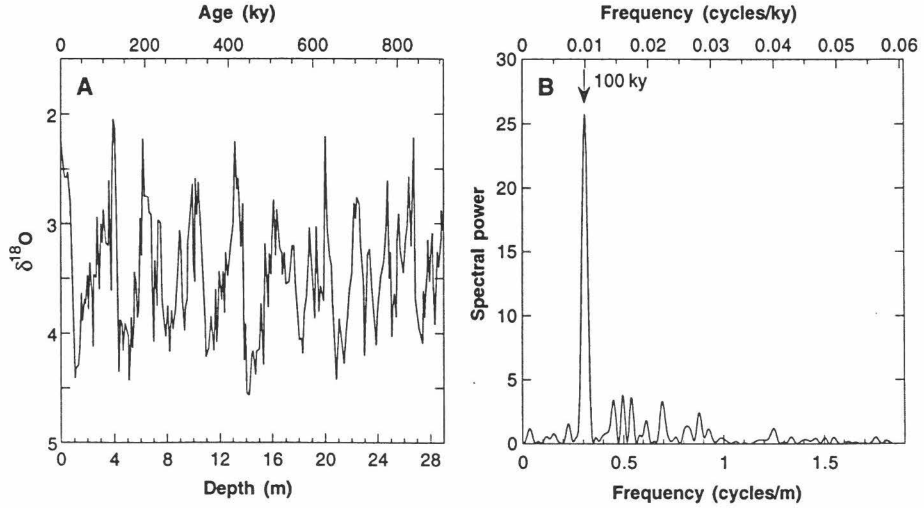

Fig. 2. (**A**) $\delta^{18}O$ data in parts per thousand and (**B**) spectral power for ODP site 659 for the interval from 0 to 900 ka. The time scale assumes a constant sedimentation rate.

The narrow width has important implications for climate models. In any climate model that depends on free oscillation, the width will be significantly broadened if substantial energy loss (friction) is present or if the mode of oscillation is not isolated from other modes. For this reason, free-oscillation climate models generally predict broad spectral peaks. Likewise, climate models based on relaxation oscillators usually have broad peaks. Relaxation oscillators tend to lose their phase stability (and their narrow spectral peaks) unless the energy exchange mechanisms are exceptionally constant over many cycles, a condition not expected to be met in the geophysics of climate. In contrast, a climate model that depends on forced oscillations has a spectrum that reflects the spectrum of the driving force, so that regardless of losses, narrow spectral features in the force will also appear in the response (18). The only natural driving forces in physics that have narrow spectra tend to be astronomical and quantum-mechanical, because friction is often negligible both in space and in atoms. (This is why the motions of the Earth, moon, and planets provided the original calendars, and it is why quantum-mechanical devices provide the most accurate clocks.) Because we have no plausible way to relate the phase stability of the glacial cycles to quantum mechanics, we conclude that the oscillation is driven by an astronomical source. This is a general argument for the astronomical origin of the 41-ky cycle that does not depend on the details of any specific astronomical theory, such as the Croll/Milankovitch insolation model, or even on the frequency match between this cycle and the obliquity cycle.

Similar evidence for the astronomical origin of the 100-ky glacial cycle can be found in $\delta^{18}O$ data from Ocean Drilling Program (ODP) site 659, located in the Atlantic Ocean off northwest Africa, near 18°N and 21°W (19, 20). The untuned $\delta^{18}O$ data for the age interval from 0 to 900,000 years ago (ka) is shown in Fig. 2A. The time axis was derived by taking the age of Tiedeman *et al.* (20) for the maximum depth and assuming constant sedimentation. The spectrum is shown in Fig. 2B. A strong narrow peak appears near f = 0.01 cycles/ky (100-ky period). The FWHM of the peak is $\Delta f/f$ = 9.8%, which is indistinguishable from the width one would obtain for a sine wave (16). It is highly unlikely that a single narrow peak would appear in the untuned data unless the sedimentation rate were relatively constant and there were a driving force with a strong single period. We conclude that the 100-ky cycle is astronomically driven.

To make a more comprehensive study of the 100-ky cycle and to compare it with theory, we examined $\delta^{18}O$ records for cores at the following DSDP and ODP sites located in the Atlantic, Pacific, and Indian oceans: site 552 (*21*), site 607 (*7, 9*), site 659 (*19, 20*), site 664 (*22*), site 677 (*23, 24*), site 806 (*25, 26*), site 849(*27*), and the Specmap stack (*28*). Site 806 has been shown to have a nearly constant sedimentation rate for the interval from 0 to 840 ka (*29*). A narrow peak in the untuned data, which is evidence for nearly constant sedimentation, was also found in the spectra for site 664 for the interval from 0 to 600 ka.

In order to facilitate comparisons among the sites, we chose a common time interval covered by all the $\delta^{18}O$ data sets: 0 to 600 ka. In column A of Fig. 3 we show the spectra for this period expected from three climate models: a linear eccentricity model, a nonlinear ice model that derives its quasi–100-ky cycle from the envelope of the precession parameter (*30*), and an orbital inclination model (*31–33*). The frequency scale has been expanded to facilitate comparisons of the peak shape and structure. The orbital spectra were calculated using the results of Quinn *et al.* (*34*). The orbital inclination was transformed to the invariant plane as described by Muller and MacDonald (*33*); the values for the past 3 million years have been posted on the World Wide Web at www-muller.lbl.gov. The insolation-based models have spectral fingerprints with three peaks near 0.0025, 0.008, and 0.0105 cycles/ky, corresponding to periods of 400, 125, and 95 ky. The fingerprint of the inclination model has a single prominent peak near frequency 0.01 cycles/ky, corresponding to a period of 100 ky

The spectra of the $\delta^{18}O$ data are plotted in the remaining columns of Fig. 3. Column B contains the spectra for the sites at which there was evidence (as discussed above) that the sedimentation rate was nearly constant: sites 659, 664, and 806. Column C contains the data for which the sedimentation rate showed evidence of variability during the 0- to 600-ka interval but for which a minimally tuned time scale was available: sites 552, 607, and Specmap. (By minimally tuned, we mean that the sedimentation rate was tuned, at most, to obliquity and precession, but that there was no 100-ky cycle in the target curve. Such tuning can artificially enhance and narrow the 41- and 23-ky peaks; if done badly, it could destroy the 100-ky peak, but it is unlikely to artificially narrow the 100-ky peak.) Column D has spectra of data that showed strong evidence for sedimentation rate variability and for which the only time scale that had been published was tuned to a climate model that included eccentricity.

There is a remarkably consistent pattern in the $\delta^{18}O$ spectral fingerprints in Fig. 3. All show a single narrow peak near frequency 0.01 cycles/ky (period 100 ky), which is similar to the spectrum of the orbital inclination model. None of the spectra show the multiple peak structure expected from the insolation theories. Even the fully tuned data sets in column D, which are suspect because they were tuned to eccentricity, are a better match to the inclination model than to the eccentricity or nonlinear ice models. This evidence suggests that orbital inclination is the primary driving force for the global ice proxy $\delta^{18}O$ during the past million years, although we cannot rule out a small contribution by eccentricity or precession. Several of the spectra show small peaks near $f = 0.008$ (period 125 ky), which are characteristic of the insolation models, but these peaks have low statistical significance and could be noise fluctuations. None of the $\delta^{18}O$ data show either the expected doublet (125- and 95-ky periods) or the strong peak near $f = 0.0025$ (400-ky period) that is present in the insolation models. It has been argued that the 400-ky cycle can be suppressed by the geologic response (*35*). However, there are at least two other climate records, unrelated to glacial volume, that show the complete triplet structure expected from eccentricity (400-, 125-, and 95-ky peaks): the coarse component (large foraminifera fraction) of sediment at site 806 (*29*) and Triassic lake-bed depth ranks (*36*). These examples show that the 400-ky peak is not necessarily suppressed by the Earth response, and so its absence from the $\delta^{18}O$ record must be considered additional evidence against eccentricity or precession as a driving force for variations in global ice volume. These examples also show that eccentricity and precession do affect other aspects of climate. At site 806, signals from inclination and eccentricity were found to be present simultaneously (*29*). However, the eccentricity signal was in a proxy thought to be sensitive to local climate (the coarse fraction of the sediment), whereas the inclination signal was in the proxy for global ice fraction ($\delta^{18}O$).

The shift of the dominant glacial cycle from 41 to 100 ky, which took place about a million years ago, can be understood if the mechanism that links orbital inclination to climate is the accretion of extraterrestrial dust. In 1994, Muller (*31*) postulated that the sudden onset of the 100-ky cycle might have been be caused by an increase in the amount of interplanetary

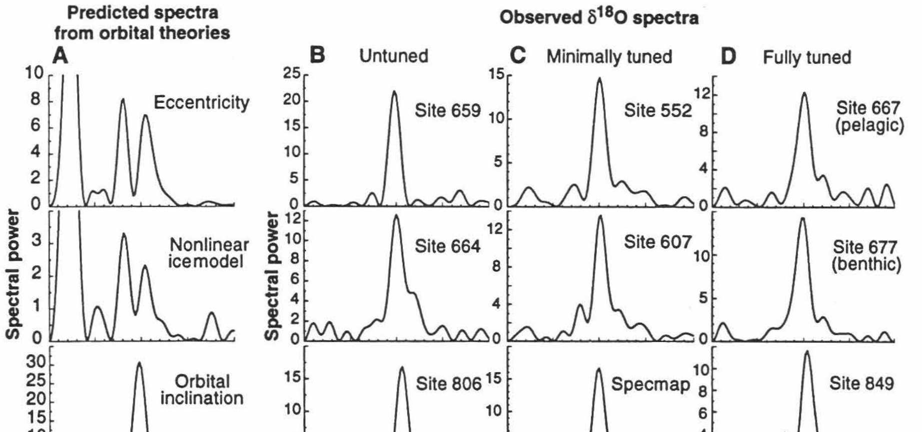

Fig. 3. Spectra of orbital models and of the $\delta^{18}O$ data (a proxy for global ice) for the interval from 0 to 600 ka. The frequency scale has been expanded to facilitate comparison of peak shapes near 0.01 cycles/ky (period, 100 ky). Column (**A**) shows spectra of three possible drivers for the glacial data: a linear eccentricity model, a nonlinear ice model that derives the 100-ky signal from the envelope of precession parameter, and an orbital inclination model. The next three columns show the spectral power of $\delta^{18}O$ data. Column (**B**) shows data with untuned time scales. Column (**C**) shows data with minimally tuned time scales (tuned to periods of 41 and 23 ky). Column (**D**) shows data with fully tuned time scales, that is, the target climate model included an explicit 100-ky eccentricity cycle. All the data show a similar pattern: a single narrow peak near frequency $f = 0.01$ cycles/ky (period, 100 ky), which is in good agreement with the orbital inclination theory and in disagreement with the complex spectra predicted by the eccentricity- and precession-based theories.

dust or meteoroids at that time. An abrupt increase in accreted dust at about 1 Ma was subsequently reported by Farley in a study of ^{3}He in sediment (*37*). When accretion was low, the dominant driving force for glaciation was obliquity, perhaps through a Croll/Milankovitch insolation mechanism. After the dust increase, the 41-ky obliquity cycle continued but was obscured under the stronger dust-driven inclination cycles. The strongest cycle predicted by many insolation models has a period of 23 ky. Yet this cycle is weak in all the $\delta^{18}O$ records we have studied. This cycle would be naturally suppressed, even when insolation is the dominant driving force of glaciation, if ice volume is not particularly sensitive to the north/south land mass asymmetry on Earth. Previous insolation mechanisms could not invoke this suppression because they required a strong precession contribution in order to account for the 100-ky cycle; a cycle we attribute instead to inclination.

One of the predictions of the accretion theory was that 100-ky cycles in dust or meteoric material could be found in sedimentary material or glacial ice, although an initial search failed to achieve sufficient sensitivity (*31*). To test this prediction, Farley searched for cycles of ^{3}He in sediment and found the predicted 100-ky cycle, with the times of high accretion being roughly coincident with the interglacials (*38*). It is possible that the bulk of the dust would have a different phase. The ^{3}He measurements are sensitive primarily to dust particles with a diameter of about 7 μm, whereas most of the accretion comes from particles larger than 50 μm (*39*). The orbits of the dust particles depend strongly on size, because their path to Earth is determined primarily by the Poynting-Robertson effect (viscosity from sunlight), and while enroute to Earth, their orbits are perturbed by Jupiter and the other planets.

A narrow ring of dust around the sun was detected by the Infrared Astronomical Satellite (*40, 41*). This ring is within 1/2 degree of the dust band assumed in the accretion model. According to Dermott *et al.* (*42*), this dust is continually replenished by collisions among the members of the Themis and Koronis asteroid families. Kortenkamp *et al.* (*43*) have calculated that most of the extraterrestrial accretion on Earth comes from this narrow solar ring. The event a million years ago that increased the rate of injection of interplanetary dust could have been a particularly disruptive collision in the Themis or Koronis families. According to Kortenkamp *et al.* (*43*), the cyclicity of accretion observed by Farley is a necessary consequence of the known dust orbits combined with orbital calculations.

Although the $\delta^{18}O$ spectra imply that the global ice volume is forced predominately by orbital inclination and obliquity, other aspects of climate seem to be driven by eccentricity or precession. Thus it appears that glacial cycles are not completely synonymous with climate cycles. It will be a challenge to future geophysical models to account for the dichotomy.

REFERENCES AND NOTES

1. J. Croll, *Philos. Mag.* **33**, 426 (1867).
2. ______, *Climate and Time* (Appleton, New York, 1875).
3. M. Milankovitch, *Théorie Mathématique des Phénomènes Produits par la Radiation Solaire* (Gauthier-Villars, Paris, 1920).
4. ______, *Canon of Insolation and the Ice-Age Problem*, Royal Serbian Academy Special Publication 132 (Royal Serbian Academy, Belgrade, Yugoslavia, 1941).
5. W. S. Broecker and J. van Donk, *Rev. Geophys. Space Phys.* **8**, 169 (1970).
6. J. Hays, J. Imbrie, N. Shackleton, *Science* **194**, 1121 (1976).
7. W. F. Ruddiman, M. E. Raymo, D. G. Martijnson, B. M. Clement, J. Backman, *Paleoceanography* **4**, 353 (1989).
8. B. U. Neeman, "Orbital Tuning of Paleoclimatic Records: a Reassessment" (Lawrence Berkeley National Laboratory Report LBNL-39572, Berkeley, CA, 1993).
9. M. E. Raymo, W. F. Ruddiman, J. Backman, B. M. Clement, D. G. Martinson, *Paleoceanography* **4**, 413 (1989).
10. W. F. Ruddiman, M. Raymo, A. McIntyre, *Earth Planet. Sci. Lett.* **80**, 117 (1986).
11. R. B. Blackman and J. W. Tukey, *The Measurement of Power Spectra* (Dover, New York, 1958).
12. The Blackman-Tukey method obtains the spectral power by first forming the autocorrelation function of the data and then performing a Fourier transform. If only a partial autocorrelation is performed, for example, if the maximum delay is only 1/3 of the time interval of the data set, then we say the "lag" is 1/3. The spectral peak in the lagged analysis is broadened by a factor equal to 1/lag.
13. Spectral power is computed by interpolating the data to equally spaced points, removing the average (but not the trend), using a boxcar window (that is, taking all points equally weighted), and then taking the square of the Fourier transform. The spectrum is normalized to unit mean. The data presented here have also been examined with other spectral methods (such as Blackman-Tukey with various lags, and Lomb-Spergel) and other windows (such as Hanning and Parzen). The conclusions are robust to all data methods, excluding those that significantly degrade the resolution and therefore could not resolve the narrow features from which we draw our conclusions.
14. The background spectral power in the vicinity of this peak is 1.5; the height of the peak is 18.5; this means that the peak is significant at the level of exp(−18.5/1.5) = 4×10^{-6}. Because there are approximately 50 independent frequencies in the plot, the confidence level for this peak is CL = 1 − (50) (4×10^{-6}) = 99.98%.
15. The age of 1.5 Ma corresponds to an adjusted depth of 66.83 m, and the age of 2.5 Ma corresponds to an adjusted depth of 112.40 m. These give an average sedimentation rate of 45.6 m per million years.
16. The FWHM Δf of the spectral peak that results from calculating the spectral power of a pure sine wave (or any other perfectly periodic signal) of duration T, is $\Delta f = 0.886/T$. This width could be made larger by applying a window to the data (such as a Hanning window) that deemphasizes data at the beginning and end of the interval; the width can be made smaller by applying a window that emphasizes the two ends of the interval. In this paper we weight all data equally; this is sometimes called a flat or a boxcar window. For a 600-ky interval, the width is $\Delta f = 0.886/600 = 1.5 \times 10^{-3}$ cycles/ky; the separation of the components of the 95/125 eccentricity doublet is significantly larger: 2.5×10^{-3} cycles/ky. For a 900-ky interval, the width is $\Delta f = 9.8 \times 10^{-4}$ cycles/ky.
17. The frequency of oscillation is $f = 1/P$, where P is the period; the FWHM is $\Delta f = 0.886/T$, where T is the duration of the interval. Therefore the fractional width is $\Delta f/f = (0.886/T)P = 0.886/N$, where $N = T/P$ is the number of cycles in the interval T.
18. The response may have a different phase than the driving force, but it has the same frequency, even if several resonances are present. For a simple introduction to some of the properties of forced and free oscillations, see J. B. Marion and S. T. Thornton, *Classical Dynamics of Particles and Systems* (Harcourt Brace Jovanovich, New York, 1988).
19. M. Sarnthein and R. Tiedemann, *Proc. Ocean Drill. Program Sci. Results* **108**, 167 (1989).
20. R. Tiedemann, M. Sarnthein, N. J. Shackleton, *Paleoceanography* **9**, 619 (1994).
21. N. J. Shackleton and M. A. Hall, in *Initial Reports of the Deep Sea Drilling Project* (U.S. Government Printing Office, Washington, DC, 1984), vol. 81, pp. 599–609.
22. M. E. Raymo, D. W. Oppo, W. Curry, *Paleoceanography*, in press.
23. N. J. Shackleton and M. A. Hall, *Proc. Ocean Drill. Program Sci. Results* **111**, 295 (1989).
24. J. J. Shackleton, A. L. Berger, W. R. Peltier, *Trans. R. Soc. Edinburgh Earth Sci.* **81**, 251 (1990).
25. W. H. Berger, T. Bickert, H. Schmidt, G. Wefer, *Proc. Ocean Drill. Program Sci. Results* **130**, 381 (1993).
26. W. H. Berger, M. K. Yasuda, T. Bickert, G. Wefer, T. Takayama, *Geology* **22**, 463 (1994).
27. A. C. Mix *et al.*, *Proc. Ocean Drill. Program Sci. Results* **138**, 371 (1991).
28. J. Imbrie *et al.*, in *Milankovitch and Climate, Part 1*, A. Berger *et al.*, Eds. (Riedel, Dordrecht, Netherlands, 1984), pp. 269–305.
29. R. A. Muller and G. J. MacDonald, *Geology* **25**, 3 (1997).
30. J. Imbrie and J. Z. Imbrie, *Science* **207**, 943 (1980).
31. R. A. Muller, "Glacial Cycles and Extraterrestrial Accretion" (Lawrence Berkeley Laboratory Report LBL-35665, Berkeley, CA, 1994).
32. ______ and G. J. MacDonald, *Nature* **377**, 107 (1995).
33. ______, *Proc. Natl. Acad. Sci. U.S.A.*, in press.
34. T. R. Quinn, S. Tremaine, M. Duncan, *Astron. J.* **101**, 2287 (1991).
35. J. Imbrie *et al.*, *Paleoceanography* **8**, 699 (1993).
36. P. E. Olsen and D. V. Kent, *Palaeogeogr. Palaeoclimatol. Palaeoecol.* **122**, 1 (1996).
37. K. Farley, *Nature* **376**, 153 (1995).
38. ______ and D. B. Patterson, *ibid.* **378**, 600 (1995).
39. K. A. Farley, S. G. Love, D. B. Patterson, *Geochim. Cosmochim. Acta.*, in press.
40. M. Sykes, *Astrophys. J.* **334**, L55 (1988).
41. M. V. Sykes *et al.*, in *Asteroids II*, T. G. R. Binzel and M. Matthews, Eds. (Univ. of Arizona Press, Tucson, AZ, 1989), p. 336.
42. S. F. Dermott *et al.*, *Nature* **312**, 505 (1984).
43. S. J. Kortenkamp, S. F. Dermott, J. C. Liou, in *Physics, Chemistry, and Dynamics of Interplanetary Dust*, B. Gustafson and M. Hanner, Eds. (Astronomical Society of the Pacific, San Francisco, CA, 1996), vol. 104, pp. 167–170.
44. We thank W. Alvarez and the Renaissance Geology Group for many stimulating discussions, and M. Raymo, W. Berger, M. Yasuda, P. Olsen, and S. Clemens for providing data in digital form. Additional data were obtained over the World Wide Web from the site maintained by the National Oceanic and Atmospheric Administration at www.ngdc.noaa.gov. Supported in part by the Department of Energy (under contract DE-AC03-7bSF00098) and by the Ann and Gordon Getty Foundation.

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Spectrum of 100-kyr Glacial Cycle: Orbital Inclination, not Eccentricity

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Spectrum of 100-kyr glacial cycle: Orbital inclination, not eccentricity

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ABSTRACT Spectral analysis of climate data shows a strong narrow peak with period ≈100 kyr, attributed by the Milankovitch theory to changes in the eccentricity of the earth's orbit. The narrowness of the peak does suggest an astronomical origin; however the shape of the peak is incompatible with both linear and nonlinear models that attribute the cycle to eccentricity or (equivalently) to the envelope of the precession. In contrast, the orbital inclination parameter gives a good match to both the spectrum and bispectrum of the climate data. Extraterrestrial accretion from meteoroids or interplanetary dust is proposed as a mechanism that could link inclination to climate, and experimental tests are described that could prove or disprove this hypothesis.

Using much improved dating techniques, Broecker and van Donk (1) in 1970 conclusively established that the dominant cycle in proxy climate records is 100 kyr. Broecker and van Donk did not commit themselves as to the origin of the 100-kyr cycle. In the years after 1970, it became customary to attribute the 100,000-year cycle to variations in the orbital eccentricity of the earth (2). Calculated variation of eccentricity shows a quasi-periodic behavior, with a period of about 100 kyr. Milankovitch (3, 4) proposed that eccentricity affected the climate through its effect on insolation: the average solar energy reaching the earth. In this paper we note five sets of observations which conflict with the suggestion that insolation variations associated with eccentricity are responsible for the dominant 100,000-year cycle.

First, the eccentricity changes are small, between 0.01 and 0.05. The resulting changes in insolation are far too small to account for the dominant 100,000-year cycle observed in proxy climate records. Second, the orbital calculations which can be carried out with great accuracy back to several million years (5) show that the major cycle in eccentricity is 400,000 (400 kyr), rather than 100 kyr. A 400-kyr fluctuation is absent in most climate records, leading to specific disagreement between eccentricity and glacial data at both 400 ka and the present (the "stage 1" and "stage 11" problems). Many proposed explanations for the discrepancies have been advanced; in a recent review, Imbrie *et al.* (6) give a short list consisting of seven groups of models. Many of the models involve resonant or nonlinear behavior of the ice–ocean–atmosphere system; some derive the 100-kyr period from the envelope of the variation in the precession parameter.

Well-dated climate proxy records show the 100,000-year cycle only over the last million years (7). Prior to this transition, the 100-kyr period is either absent or very weak. Calculated variation of eccentricity does not show any discontinuity a million years ago. If the eccentricity drove changes in insolation, it would be anticipated that variations in insolation due to changes in eccentricity would affect climate in earlier periods, as well as over the past million years.

Since methods of dating have improved, a fourth possible problem with the Milankovitch insolation has developed: several recent observations suggest that the abrupt termination of the ice ages preceded warming from insolation (8), an effect we refer to as "causality problem." The interpretation of these results is still controversial (9–13). Furthermore, Imbrie *et al.* (9) argue that a true test of the Milankovitch theory must be performed in the frequency domain, not the time domain.

The fifth problem with the Milankovitch insolation theory is found in the frequency domain. In this paper, we present a full resolution spectral analysis of $\delta^{18}O$ proxy climate records. The analysis shows that the 100-kyr period is a single, narrow peak, a simple pattern that strongly confirms an astronomical origin, but which cannot be reconciled with any of the models presented in the review by Imbrie *et al.* (6) In contrast, an alternative model that we have proposed, which attributes the 100-kyr cycle to orbital inclination, passes all the spectral tests that the Milankovitch model fails (14).

Climate Proxy Records

The isotopic composition of the oxygen isotopes in sediment is believed to reflect the percentage of earth's water frozen in ice, and thus changes in the oxygen–isotope ratio $\delta^{18}O$ are measures of the earth's climate. While we have examined a large number of records to test our conclusions, we use two primary records in this analysis: from ocean drilling project site 607 (15) and the Specmap (16) compilation. We chose these records because both had time scales that had not been tuned to match a presumed 100-kyr eccentricity cycle. Such tuning, had it been done, could have artificially narrowed the width of the 100 kyr spectral peak. The $\delta^{18}O$ signals for these data for the past 600 kyr are shown in Fig. 1 *a* and *b*. The similarity between the two records is evident; the dominant feature is the 100-kyr cycle. The spectra for these data are shown in Fig. 1 *c* and *d*. For site 607, which has unevenly spaced data, the spectrum is calculated using the methods of Lomb (17) and MacDonald (18); however, we obtained essentially identical results using interpolation and data taper followed by standard Fourier transform or by the Blackman–Tukey method (provided full lags were used).

The Milankovitch model attributes the peak near 0.01 cycles per kyr (100-kyr period) to variations in the earth's eccentricity. The 0.024 cycles per kyr peak (41-kyr period) to changes in the obliquity (tilt of the earth's axis with respect to the ecliptic), and the 0.04 cycles per kyr peak (23-kyr period) to changes in the precession parameter (delay between perihelion and summer solstice). Note that the full width at half maximum (FWHM) of the 0.01 cycles per kyr peak (100-kyr period) is 0.0016 cycles per kyr, near the theoretic minimum width (0.0015 cycles per kyr) that can be obtained with a record of

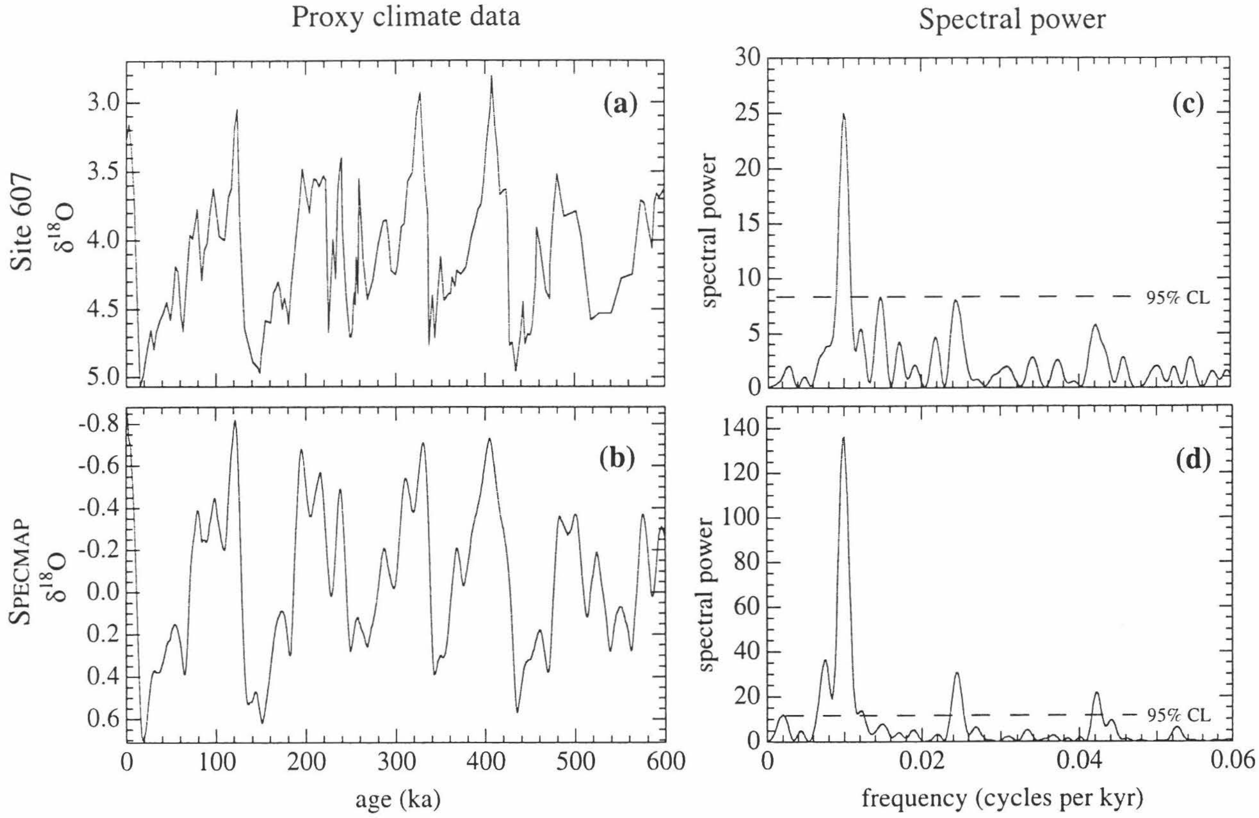

FIG. 1. δ^{18}O for past 800 kyr. (*a*) Data of site 607 from Ruddiman *et al.* (15). (*b*) Specmap stack of Imbrie *et al.* (16). (*c*) Spectral power of site 607. (*d*) Spectral power of Specmap. In the Milankovitch theory, the peak near 0.01 (100-kyr period) is attributed to eccentricity, the peak near 0.024 (41-kyr period) to obliquity, and the peak near 0.043 (23-kyr period) to precession.

600-kyr length. A re-analysis of the original pacemaker core stack with full resolution also produces a single narrow peak (FWHM = 0.0019), which is the theoretically minimum width for a record of 464 kyr length. Likewise, the spectral analysis of data from site 806 (19) shows a single narrow peak.

The narrow width of the 100-kyr peak strongly suggests a driven oscillation of astronomical origin. In contrast to dynamical astronomy, where dissipative processes are almost nonexistent, all known resonances within the earth–atmosphere system have energy transfer mechanisms that cause loss of phase stability. Narrowness of the 41-kyr and 23-kyr cycles is not necessarily significant, since the time scale of the data was tuned by adjusting the sedimentation rate to match the expected orbital cycles. The 100-kyr peak is incoherent with these other two cycles, there is no phase relationship. The fact that an unrelated peak is sharp can be considered as an *a posteriori* evidence that the tuning procedure yielded a basically correct time scale, although it could be incorrect by an overall stretch factor and delay. We did not anticipate the narrowness of the 100-kyr peak, assuming, as others have done, that it was due to forcing by variations in eccentricity. However, it is not easily reconciled with any published theory. The narrowness of the peak was missed in previous spectral analysis of isotopic data because of the common use of the Blackman–Tukey algorithm (20), which, as usually applied (lag parameter = 1/3), artificially broadens narrow peaks by a factor of 3. The Blackman–Tukey algorithm gained wide use in the 1950s because of Tukey's admonition that analysts could be misled by using classical periodograms in analyzing spectra having a continuous spectrum. For analysis of glacial cycles, these considerations did not arise, because the spectra are mixed spectra with very strong quasi-periodic peaks. Spectra of glacial cycles, as Tukey recognized, lend themselves to the use of conventional Fourier transforms.

The region of the 100-kyr peak for the δ^{18}O data is replotted in Fig. 2 *a* and *b* with an expanded frequency scale. These plots can be compared with the spectral power of the eccentricity variations, shown in Fig. 2*c*, calculated from the detailed computations of Quinn *et al.* (5). Three strong peaks are present in the eccentricity spectrum: near 0.0025 cycles per kyr (400-kyr period), near 0.08 cycles per kyr (125-kyr period), and near 0.0105 cycles per kyr (95-kyr period). The disagreement between the spectrum of climate and that of eccentricity is evident. The absence of the 400-kyr peak in the climate data has long been recognized (for a review, see Imbrie *et al.* (6), and numerous models have been devised that attempt to suppress that peak.

We note that the 100-kyr peak is split into 95- and 125-kyr components, in serious conflict with the single narrow line seen in the climate data. The splitting of this peak into a doublet is well known theoretically (22), and results from the phase-coherent modulation by the 400-kyr peak. But in comparisons with data, the two peaks in eccentricity were made into a single broad peak by the enforced poor resolution of the Blackman–Tukey algorithm. The single narrow peak in the climate data was likewise broadened and the resulting comparisons led to the belief that the theoretical eccentricity and the observed climate data were very much alike.

The disagreement between the data (Fig. 2 *a* and *b*) and the theory (Fig. 2 *c* and *d*), cannot be accounted for by experimental error uncertainty. Tuning of the time scale to a specific peak (by adjusting the unknown sedimentation rates) can artificially narrow that peak as other peaks that are coherent with it [see, for example, Neeman (23)]. However, the data in Fig. 2 *a* and *b* were tuned only to peaks obliquity and precession that are incoherent with the 100-kyr eccentricity cycle, so that tuning cannot account for the narrow width. Likewise, chatter (errors in the time scale from mis-estimated sedimentation

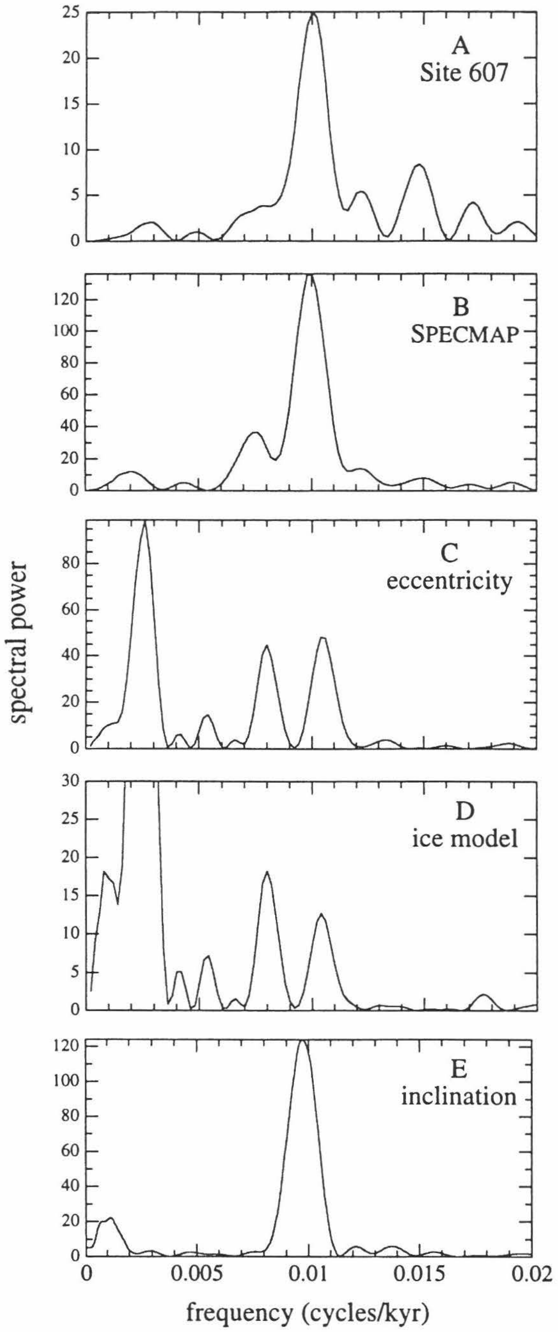

FIG. 2. Spectral fingerprints in the vicinity of the 100-kyr peak for data from site 607 (*a*); for data of the Specmap stack (*b*); for a model with linear response to eccentricity, calculated from the results of Quinn *et al.* (5) (*c*); for the nonlinear ice-sheet model of Imbrie and Imbrie (21) (*d*); and for a model with linear response to the inclination of the Earth's orbit (measured with respect to the invariable plane) (*e*). All calculations are for the period 0–600 ka. The 100-kyr peak in the data in *a* and *b* do not fit the fingerprints from the theories *c* and *d*, but are a good match to the prediction from inclination in *e*.

rates) cannot reconcile the disagreement, since although chatter can smear a doublet into a single broad peak, it will not turn a doublet into a single narrow peak. Could a physical mechanism convert a 95- to 125-kyr doublet into a single narrow peak? Dissipative mechanisms could obscure the doublet, but (like chatter) they yield a single broad peak or a cluster of doublets. Resonances used to suppress the 400-kyr peak are not sharp enough to suppress one element of the narrow doublet. In principle, a strong nonlinear process could turn a doublet into a single peak, as it does (for example) in a laser; however, no such mechanism has been identified in the lossy, friction-filled environment of the earth and its atmosphere.

Several nonlinear models reviewed by Imbrie *et al.* (6) derive the 100 kyr cycle from the envelope of the precession cycle. However, this envelope also has a split peak, since it derives ultimately from eccentricity (the envelope of the precession is the eccentricity). As an example, we show the spectrum of the ice sheet model of Imbrie and Imbrie (21) in Fig. 2*d*. As expected, it too shows the 95- to 125-kyr doublet, in disagreement with the data. None of the nonlinear models in the recent comprehensive review by Imbrie *et al.* (6) have the required laser-like mechanism, and they all predict a split peak. This is a fundamental disagreement, not fixed by adjusting parameters. Unlike the 400-kyr cycle, which is far enough mismatched from the 100 kyr to be suppressed (at least in principle) by the models, the lines in the 95–125 doublet are too close. We draw a remarkably strong conclusion that variations in the earth's eccentricity cannot be responsible for the 100-kyr cycle.

Orbital Inclination: An Alternative 100-kyr Cycle

We recently proposed that a different orbital parameter, the inclination of the earth's orbit to the invariable plane of the solar system, should be associated with the 100-kyr glacial cycle (14, 24). The invariable plane of the solar system is that plane perpendicular to the angular momentum vector of the solar system, and is approximately equal to the orbital plane of Jupiter. The dominant peak in the spectrum of the inclination is at 0.01 cycles per kyr (100-kyr period) in a remarkably close match to the 100-kyr peak observed in the climate spectra. According to theory, this 100-kyr peak is also split, but only by 10^{-3} cycles per kyr, and this cannot be resolved with the 600-kyr record length. The variation of inclination i with time is calculated using the long-term integrations of Quinn *et al.* (5) and projecting the variation of inclination to the invariable plane.

The existence of the 100-kyr cycle of orbital inclination does not seem to have been previously noted by climatologists. It may have been missed for two reasons. Ever since the work of Milankovitch, the implicit assumption has been that insolation is the driving force for climate cycles, and the insolation is not directly affected by orbital inclination. In addition, the 100-kyr cycle is not evident until the orbital elements are transferred to the natural reference plane of the solar system, the invariable plane.

The fit of orbital inclination to the $\delta^{18}O$ data from Specmap is shown in Fig. 3. Only two parameters were adjusted in the fit: one to set the relative scale between inclination and $\delta^{18}O$ and a lag representing the delayed ice response to inclination. The best fit had a lag of 33 ± 3 kyr, with inclination accounting for 43% of the variation in the $\delta^{18}O$ signal (for a record extending back 900 kyr the fit is even better, with inclination accounting for 48% of the variation) (25). Note that the inclination cycle has no 400-kyr component: the 100-kyr cycle remains strong for the last 600 kyr. Thus attribution of the cycle to inclination provides a natural (no-parameter) solution to the stage 1 and stage 11 problems as well as to the causality problems.

Bispectra

Bispectral analysis can be used to give an independent test of the causal link between a theoretical driving mechanism and a response. A peak appears in the bispectrum only if three frequencies are present in the data, and the third is not only the sum or difference of the other two, but in phase lock with the sum or difference of their phases. The bispectrum can strongly suppress noise, and it can yield a completely independent test for proposed forcing mechanisms. In Fig. 4, we show the bispectrum of orbital inclination of $\delta^{18}O$ (from

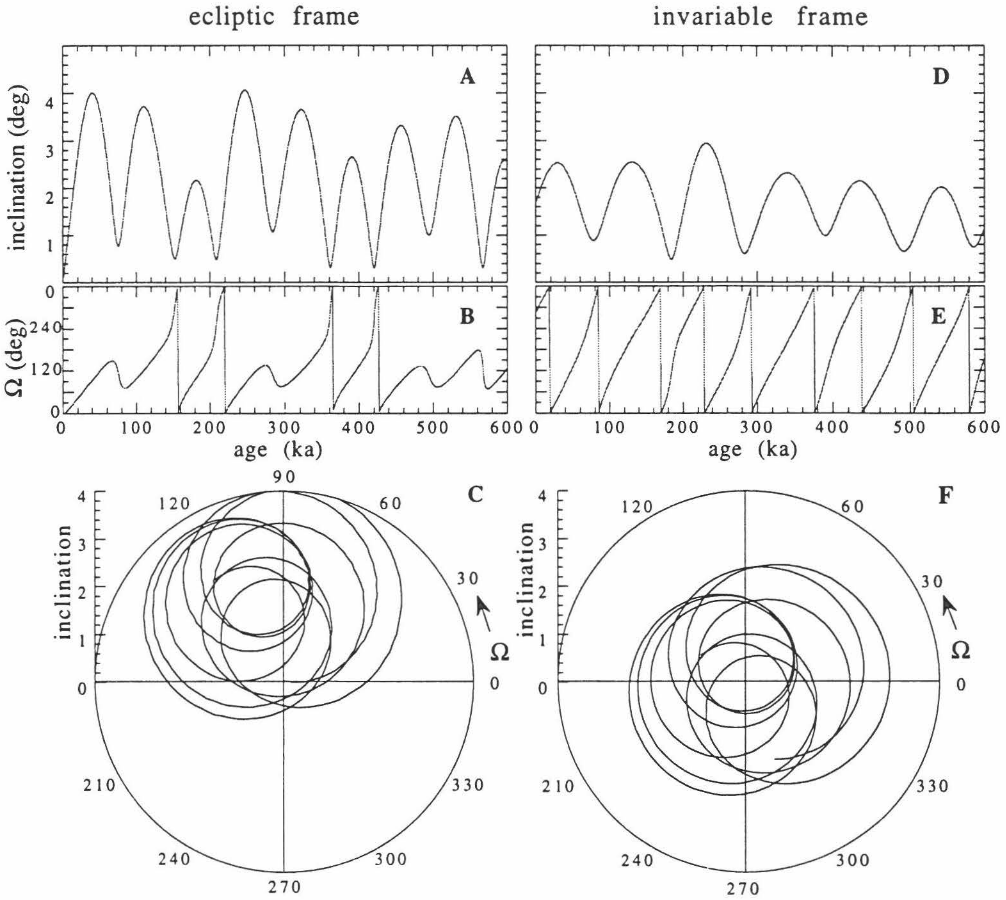

FIG. 3. Variations of the inclination vector of the Earth's orbit. The inclination *i* is the angle between this vector and the vector of the reference frame; Ω is the azimuthal angle = the angle of the ascending node (in astronomical jargon). In *A–C*, the measurements are made with respect to the zodiacal (or ecliptic) frame–i.e., the frame of the current orbit of the Earth. In *D–F*, the motion has been transformed to the invariable frame—i.e., the frame of the total angular momentum of the solar system. Note that the primary period of oscillation in the zodiacal frame (*A*) is 70 kyr, but in the invariable plane (*D*) it is 100 kyr.

Specmap) and eccentricity [Elsewhere (26, 27) we give a detailed discussion of the calculations and their interpretations.] The strongest peak in inclination (Fig. 4*a*) is at (f_1 = 0.009, f_2 = 0.001), indicating that for the orbital variations, the signals near 0.001, 0.01, and 0.009 are frequency and phase locked. This same peak appears as the most significant signal in the $\delta^{18}O$ bispectrum, confirming the hypothesis that the glacial cycles are driven by orbital inclination. In contrast, the bispectrum of eccentricity, Fig. 4*c*, shows little resemblance to the $\delta^{18}O$ bispectrum. This bispectrum also supports that climate cycles are related to orbital inclination.

Linking Mechanisms

Since orbital inclination does not affect insolation, we must search for another mechanism relating changes in orbital inclination to changes in global climate. The only plausible one we have found is accretion of interplanetary material: meteoroids and dust. As the orbit of the earth changes, it passes through different parts of the sun's zodiacal ring and encounters different regions of density of material. Changes in inclination will be reflected in changes of accretion. The meteoroids and dust will, through orbital processes, tend to concentrate in the invariable plane. As the earth passes through the invariable plane, accretion increases, and we speculate that glaciers grow, while recession of glaciers takes place during high inclinations when the earth's orbit tips out of the invariable plane. We emphasize that this mechanism is speculative, and that there is no known meteoroid or dust band that satisfies all the properties that we require, although it is possible that such a band could exist. We will offer some indirect evidence that accretion does vary with orbital inclination.

Interplanetary dust accreting on the sun has previously been proposed as a driver of the ice ages (28, 29). Clube (30) discussed the possibility of accretion from a single large and unknown meteor stream affecting earth's climate, but he did not draw any conclusions with respect to the periodicity of glacial cycles. Hoyle and Wickramasinghe (31) calculated the effect that accreting dust in the atmosphere could have on the greenhouse effect through the seeding of ice crystals, and speculated that such accretion could have been responsible for the Little Ice Age. At a meeting of the Royal Astronomical Society, reported by G. Manley (32), Hoyle discussed the possibility that accretion could remove enough atmospheric water vapor to reduce the greenhouse effect and cause cooling. Stratospheric dust could also be an effective scavenger of other greenhouse gases, including ozone, and possibly could affect the concentration of components such as chlorine that are thought to be responsible for the destruction of ozone.

The climatic effects of high-altitude dust and aerosols are known primarily from volcanic eruptions; global cooling of 0.5–1°C was estimated from the eruption of Krakatoa, and measurable climate changes have been attributed to El Chichon, Pinatubo, and other recent eruptions that injected several megatons of material into the stratosphere. Large explosive volcanic events occur typically once every century, so the average injection of volcanic material is approximately 100 kton/yr (33). Measurements by Kyte and Wasson (34) of iridium in oceanic sediments show that the long-term global

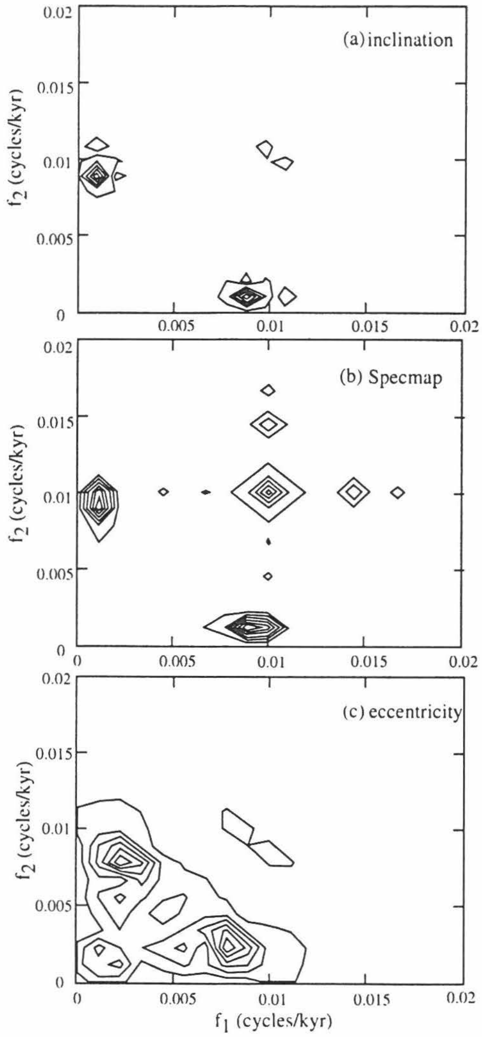

FIG. 4. Bispectra of (*a*) inclination of the earth's orbit, (*b*) δ^{18}O data from Specmap, and (*c*) the eccentricity of the earth's orbit. The inclination and eccentricity were taken from Quinn *et al.* (5) transformed to the invariable plane. Note the close match between the most significant peaks in the inclination bispectrum and δ^{18}O bispectrum. The scale is linear, and the units arbitrary; for details of the bispectral method see MacDonald and Muller (26).

average flux from extraterrestrial materials for the period 35–70 Ma is 60–120 kton/yr, about the same as the long-term average from present-day volcanic eruptions.

Accretion could cause cooling (as volcanic eruption suggests) or warming (if cometary particles inject water). Large particles (10 μm) take a few hours to reach the ground: smaller particles (0.5 μm) take a few months. Gases can reside for much longer. Extraterrestrial accretion occurs at the top of the atmosphere, so the climate effects could be significantly different from those resulting from volcanic eruptions. In addition, the global distribution of dust from the two mechanisms is different; for example, stratospheric circulation patterns rarely carry volcanic material to the poles.

Data on noctilucent clouds (mesospheric clouds strongly associated with the effects of high meteors and high altitude dust) supports the hypothesis that accretion increases significantly when the Earth passes through the invariable plane. A strong peak in the number of observed noctilucent clouds occurs on about July 9 in the northern hemisphere (35, 36) within about a day of the date when the Earth passes through the invariable plane. In the southern hemisphere the peak is approximately on January 9, also consistent with the invariable plane passage, but the data are sparse. This coincidence has not been previously noted, and it supports the contention that there is a peak in accretion at these times. On about the same date there is a similarly narrow peak in the number of polar mesospheric clouds (37) and there is a broad peak in total meteoric flux (38). It is therefore possible that it is a trail of meteors in the upper atmosphere, rather than dust, that is responsible for the climate effects.

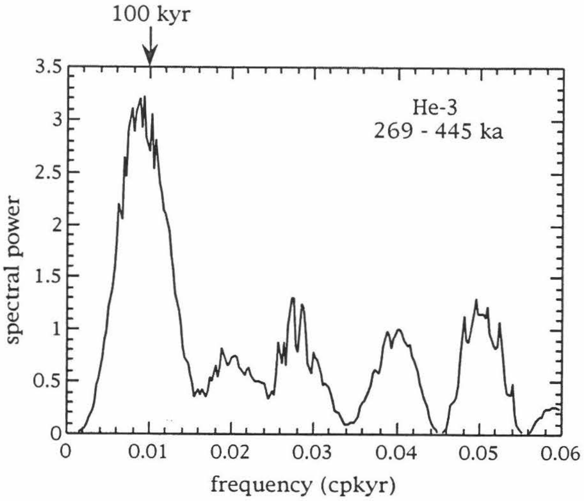

FIG. 5. Spectrum of the accretion of extraterrestrial dust for the period 269–445 ka, determined from the helium-3 measurements of Farley and Patterson (39).

Discussion

The hypothesis that variations in inclination are responsible for the 100-kyr fluctuations cleanly solves three of the difficulties associated with the hypothesis that variations in eccentricity are responsible. First, the inclination shows a single narrow peak, in agreement with the spectrum of climate proxy records. Second, the variation in inclination does not show any peak at 400 kyr, again in agreement with observations. Third, the inclination hypothesis satisfactorily deals with the causality issue.

The linkage of variations in inclination with climate suffers from the requirement that one must assume the dust concentrations to be sufficient to bring about significant changes in climate. Evidence that extraterrestrial accretion has varied with 100-kyr period is evident in the observations by Farley and Patterson (39). The spectrum of the observed accretion, as determined from fluctuations in helium-3, is plotted in Fig. 5. The only statistically significant peak is the predicted one with a period of 100 kyr. This association is suggestive, but we have not yet been able to calculate quantitatively the effect of various mechanisms of accretion on climate.

The sudden onset of the 100-kyr peak about 1 million years ago can also be dealt with by the accretion hypothesis. We are required, however, to assume that the dustiness of the solar system underwent a discontinuous change at about a million years. This would require, for example, the breakup of a large comet. Again, Farley (40) has shown that indeed there appears to be discontinuity in the rate of accretion about 1 million years ago.

We believe the inclination hypothesis is one that should be further investigated, both in terms of theory and in terms of observations of past rates of extraterrestrial accretion.

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1. Broecker, W. S. & van Donk, J. (1970) *Rev. Geophys. Space Phys.* **8,** 169–197.
2. Imbrie, J. & Imbrie, K. P. (1979) *Ice Ages, Solving the Mystery* (Harvard Univ. Press, Cambridge, MA).
3. Milankovitch, M. (1941) *Canon of Insolation and the Ice-Age Problem* (Royal Serbian Academy, Belgrade, Yugoslavia).
4. Milankovitch, M. (1920) *Théorie Mathématique des Phénomènes Produits par la Radiation Solaire* (Gauthier-Villars, Paris).
5. Quinn, T. R., Tremaine, S. & Duncan, M. (1991) *Astron. J.* **101,** 2287–2305.
6. Imbrie, J., Berger, A., Boyle, E., Clemens, S., Duffy, A., Howard, W., Kukla, G., Kutzbach, J., Martinson, D., McIntyre, A., Mir, A., Molfino, B., Morley, J., Peterson, L., Pisias, N., Prell, W., Raymo, M., Shackleton, N. & Toggweiller, J. (1993) *Paleoceanography* **8,** 699–735.
7. Ruddiman, W. F., Raymo, M. & McIntyre, A. (1986) *Earth Planet. Sci. Lett.* **80,** 117–129.
8. Winograd, I. J., Coplen, T. B., Landwehr, J. M., Riggs, A. C., Ludwig, K. R., Szabo, B. J., Kolesar, P. T. & Revesz, K. M. (1992) *Science* **258,** 255–260.
9. Imbrie, J., Mix, A. C. & Martinson, D. G. (1993) *Nature (London)* **363,** 531–533.
10. Winograd, I. J. & Landwehr, J. M. (1993) *U.S. Geological Survey Open-File* (U.S. Geological Survey, Reston, VA), Rep. USGS 93-357.
11. Ludwig, K. R., Simmons, K. R., Winograd, I. J., Szabo, B. J. & Riggs, A. C. (1993) *Science* **259,** 1626–1627.
12. Emiliani, C. (1993) *Nature (London)* **364,** 583–584.
13. Landwehr, J. M., Winograd, I. J. & Coplen, T. B. (1994) *Nature (London)* **368,** 594.
14. Muller, R. A. & MacDonald, G. J. (1995) *Nature (London)* **377,** 107–108.
15. Ruddiman, W. F., Raymo, M. E., Martijnson, D. G., Clement, B. M. & Backman, J. (1989) *Plaeoceanography* **4,** 353–412.
16. Imbrie, J., Hays, J., Martinson, D., McIntyre, A., Mix, A., Morley, J., Pisias, N., Prell, W. & Shackleton, N. (1984) in *Milankovitch and Climate Part 1*, eds. Berger, A., Imbrie, J. & Shackleton, N. (Riedel, Dordrecht, The Netherlands), pp. 269–305.
17. Lomb, N. (1976) *Astrophys. Space Sci.* **39,** 447–462.
18. MacDonald, G. J. (1989) *Rev. Geophys.* **27,** 449–469.
19. Berger, W. H., Yasuda, M. K., Bickert, T., Wefer, G. & Takayama, T. (1994) *Geology* **22,** 463–467.
20. Blackman, R. B. & Tukey, J. W. (1958) *The Measurement of Power Spectra* (Dover, New York).
21. Imbrie, J. & Imbrie, J. Z. (1980) *Science* **207,** 943–952.
22. Berger, A. & Loutre, M. (1991) *Earth Planet. Sci. Lett.* **111,** 369–382.
23. Neeman, B. U. (1993) *Orbital Tuning of Paleoclimatic Records: A Reassessment* (Lawrence Berkeley National Laboratory, Berkeley, CA), Rep. LBNL-39572.
24. Muller, R. A. (1994) *Glacial Cycles and Extraterrestrial Accretion* (Lawrence Berkeley Laboratory, Berkeley, CA), Rep. LBL-35665.
25. Muller, R. A. & MacDonald, G. J. (1994) *Glacial Cycles: Orbital Mutation Dominated for the Last 900,000 Years* (Lawrence Berkeley Laboratory, Berkeley, CA), Rep. LBL-35667.
26. MacDonald, G. J. & Muller, R. A. (1994) *Bispectral Fingerprint Identifies 100 ky Climate Cycle: Orbital Inclination* (Lawrence Berkeley Laboratory, Berkeley, CA), Rep. LBL-36214.
27. Muller, R. A. & MacDonald, G. J. (1997) *Geology* **25,** 3–6.
28. Hoyle, F. & Lyttleton, R. A. (1939) *Proc. Cambridge Philos. Soc.* **35,** 405–415.
29. McCrea, W. H. (1975) *Nature (London)* **255,** 607–609.
30. Clube, S. (1987) *Philos. Trans. R. Soc. London* **323,** 421–436.
31. Hoyle, F. & Wickramasinghe, N. C. (1991) *Nature (London)* **350,** 467.
32. Manley, G. (1953) *Nature (London)* **173,** 1206–1208.
33. Kondratyev, K. Y. (1988) *Climate Shocks: Natural and Anthropogenic* (Wiley, New York).
34. Kyte, F. T. & Wasson, J. T. (1986) *Science* **232,** 1225–1229.
35. Thomas, G. E. (1991) *Rev. Geophys.* **29,** 553–575.
36. Foyle, B. & Haurwitz, B. (1966) *Space Sci. Rev.* **6,** 279–340.
37. Thomas, G. E. & Olivero, J. J. (1989) *J. Geophys. Res.* **94,** 14673–14681.
38. Whipple, F. L. & Hawkins, G. S. (1956) *J. Meteorol.* **13,** 236–240.
39. Farley, K. & Patterson, D. B. (1995) *Nature (London)* **378,** 600–603.
40. Farley, K. (1995) *Nature (London)* **378,** 153–156.

Simultaneous Presence of Orbital Inclination and Eccentricity in Proxy Climate Records from Ocean Drilling Program Site 806

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Simultaneous presence of orbital inclination and eccentricity in proxy climate records from Ocean Drilling Program Site 806

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ABSTRACT

Ocean Drilling Program Site 806 in the western Pacific shows evidence of a remarkably constant average sedimentation rate. This feature allows us to analyze ancient climate proxies without the need for "orbital tuning," a standard procedure in prior work, but one that can lead to biased results. Spectral analysis of stable oxygen isotope ratios at this site, a proxy for global ice volume, shows a single narrow peak with a period ≈ 100 k.y., a result that supports our model which links glacial cycles to variations in the inclination of the Earth's orbit. In contrast, spectral analysis of the coarse component fraction of the sediment (primarily foraminifera) shows a structure characteristic of standard Milankovitch theory, with a triplet of peaks with periods near those expected from the Earth's eccentricity: 95, 125, and 400 k.y. Bispectral analysis confirms these linkages but suggests that orbital inclination also plays some role in the coarse fraction. From the clear presence of both signals in different proxies at the same site, we conclude that although eccentricity affected the local climate, it is orbital inclination that drove the variations in the global ice volume for the past million years.

NTRODUCTION

Oxygen isotope records in sea-floor sediment show that the Earth's glacial cycles for the past million years were dominated by a 100 k.y. period. Although the Milankovitch theory attributes his cycle to changes in the Earth's orbital eccenricity (for a detailed review, see Imbrie et al., 1993), an alternative has been suggested by Muler and MacDonald (1995), who attribute the cycle to changes in the inclination of the Earth's orbit with respect to the plane of the solar system. Although orbital inclination does not affect insoation (total sunlight hitting the Earth—the linking mechanism of the Milankovitch theory), it could affect the climate through its effect on extraterresrial accretion of meteoroids and dust. Spectral and bispectral analyses (Muller and MacDonald, 1996) confirm that the variations in oxygen isoopes, the primary proxy for global ice volume, match the single narrow peak near 100 k.y. expected from inclination variations and are in serious conflict with the triplet peak (near periods of 95, 125, and 400 k.y.) expected from eccentricity.

Nevertheless, there are strong indications in other records that the Earth's eccentricity does have an effect on climate. A study of Triassic lake beds in New Jersey, formed during a time when large glaciers were absent, shows a climate dominated by eccentricity for a period of several million years (Olsen and Kent, 1996). All three peaks of the eccentricity triplet are clearly present in their "depth rank" data, a proxy for lake depth. This result presents us with a puzzle. Why does the eccentricity triplet appear to dominate some climate records, but not the recent cycles of glaciation?

Although the spectra of eccentricity and inclination are quite different, they are remarkably easy to confuse for two reasons: First, it has become traditional to ignore the absence of the expected 400 k.y. eccentricity cycle because it is difficult to see in the short records, and plausible effects have been postulated that could suppress it. Second, if there are variations in sedimentation rate ("chatter"), then the 95–125 k.y. doublet from eccentricity can be blurred into a single broad peak, indistinguishable from the 100 k.y. single narrow peak of inclination; similarly, chatter can break a narrow peak into an apparent doublet. Spectral analysis is less sensitive to chatter if done with low resolution, (e.g., by applying the Blackman-Tukey method with lags of ⅓); the danger is that this procedure blurs the eccentricity doublet into a single wide peak even if chatter is absent.

Attempts to compensate for the chatter have been made by using orbital tuning, a process that adjusts modeled sedimentation rate to make the geologic data match an orbital model. However, the very process of such tuning can force the record to match the target spectrum (Muller and MacDonald, 1996; a similar result has been obtained independently by Neeman, 1992), leading to a possibly mistaken linkage between the climate and the orbital parameter present in the tuning target.

In this paper we present results from a location that does not require tuning: Ocean Drilling Program (ODP) Site 806. In their initial work on this site, Berger et al. (1993) concluded that the sedimentation rate was remarkably constant; in their determination of the time scale, only minor adjustments were required. For example, for the past 900 k.y., their deduced sedimentation rate was constant within 6.5% rms (root-mean-square deviation from average). As we shall show below, the constancy of sedimentation at Site 806 is strongly supported by the appearance of extremely narrow spectral lines in the oxygen isotope data. The absence of strong variations in rate of sedimentation allows us to study the spectra of climate proxies in the core without orbital tuning—an invaluable feature if we are to identify and understand the orbital parameters that affect climate. We will show that *both* inclination and eccentricity effects are present in the Site 806 data and that they can be distinguished.

DATA

Site 806B is close to the equator (lat 0°19.1′N, long 159°21.7′E, 2520 m depth), on the Ontong Java Plateau in the western Pacific (Shipboard Scientific Party, 1991). In this paper we report (1) a new analysis of the measurements originally reported by Berger et al. (1993), consisting of oxygen isotope measurements of the fossil planktic foraminifera *Globigerinoides sacculifer*, and (2) an analysis of measurements of the mass fraction of the coarse component in the sediment (sand-sized fraction—composed primarily of large, undifferentiated foraminifera) from the same site.

$\delta^{18}O$ is defined as the fractional change in $^{18}O/^{16}O$ in parts per thousand; its variations in the ocean are driven primarily by changes in the volume of global ice, which is depleted in ^{18}O. We used two determinations for the depth of the samples. The first was to set the depth to the "driller's depth" at the top of each core segment, assume no gaps between segments, and use linear interpolation in between. We call this the "adjusted depth"; there were no adjustable parameters in its determination. The second method was to adopt the scale developed by Berger et al. (1993), who argued that gaps were present between the core segments and corrected for them by patching data from an adjacent core. The largest patch was for an assumed 75 cm gap near the depth 16 m. We refer to this depth scale as the "patched depth." The conclusions that we present in this paper are independent of which of these two depth scales we use.

The δ^{18}O and coarse component data are shown in Figure 1 as a function of adjusted depth. The spectral power for these data are shown in Figure 2. The analysis shown was performed with an unwindowed Fourier transform after interpolation to uniformly spaced points with zero padding to provide intermediate frequencies (MacDonald, 1989); the average spectral power is normalized to unity.

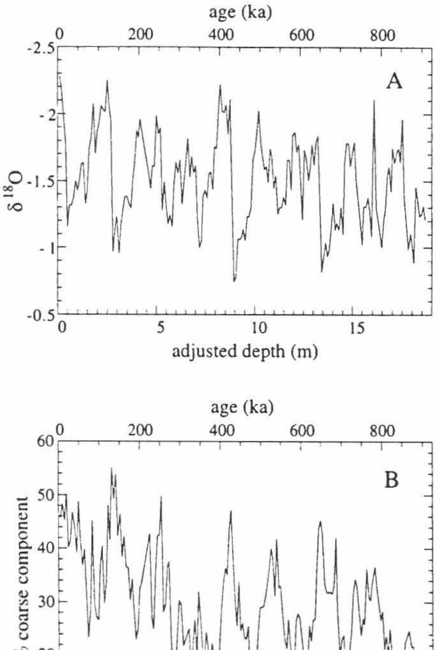

Figure 1. Climate proxies vs. adjusted depth: (A) δ^{18}O of pelagic foraminifer *G. sacculifer*; (B) coarse percentage, defined as fractional weight of coarse component ("sand," primarily forams). Data from Berger et al. (1993); adjusted depth was calculated by us and includes no correction for gaps. Time scales at top of each figure are based on (1) assumption that sedimentation rate was constant, as explained in text, and (2) placement of beginning of isotope stage 19 at Brunhes-Matuyama boundary age of 783 ka.

The spectrum of the δ^{18}O data is dominated by a strong, narrow peak near 0.47 cycles per meter. It is narrow and not split, with full width at half maximum of 10%, the same as would be obtained for a pure sine wave for the same duration. This means that the signal maintains phase coherence for the entire ≈900 k.y. period. Independent of the interpretation of the peak, the narrow width provides strong a postiori confirmation that the sedimentation rate was constant.

TIME SCALE

Time scales have been developed for these data by Berger et al. (1993, 1994, 1995) based on tuning to assumed linkage with standard Milankovitch orbital frequencies. In Berger et al. (1993), the data were filtered to a band near 41 k.y. period, the calculated variations of obliquity (the tilt of the Earth's axis with respect to the Earth's orbital plane). Approximately twenty parameters were then adjusted to achieve a match between the band-limited data and the obliquity target. In Berger et al. (1994, 1995), the target was a more complex insolation model, which included cycles with periods near 125, 95, 41, 23, and 19 k.y.

Tuning, however, can create false spectral lines that match the lines of the target spectrum, as was shown in detail by Neeman (1992). When phase coherence is achieved between the data and the target, the spectrum of the data takes on the same spectrum as the target; in addition, the narrow-band amplitude modulation of the target signal is often reproduced. In a previous analysis (Muller and MacDonald, 1996) we argued for "minimal tuning," i.e., tuning only to frequencies that were not being studied. However, the nearly constant sedimentation rate displayed at Site 806 gives us a unique opportunity to study the climate signal without the biases that might be introduced by tuning. To do this we assumed an absolutely constant sedimentation rate and set the beginning of oxygen isotope stage 19 (the peak seen at the adjusted depth 16.1 m in Fig. 1A) to the age of 783 ka for the Brunhes-Matuyama (B-M) boundary (Baksi et al., 1992). This single adjustment results in the time scale that appears at the top of Figure 1, A and B, and in the frequency scale used in the top of Figure 2, A and B.

We do not claim that this is a precise time scale, for two reasons. First, although the determination of the age of the Brunhes-Matuyama boundary by Baksi et al. (1992) has small analytic errors (±11 k.y.), they pointed out that there are possibly large systematic uncertainties from errors in the ages of the standards and in the values of the decay constants. Second, it is unlikely that the sedimentation rate was precisely constant, especially when one considers the observed

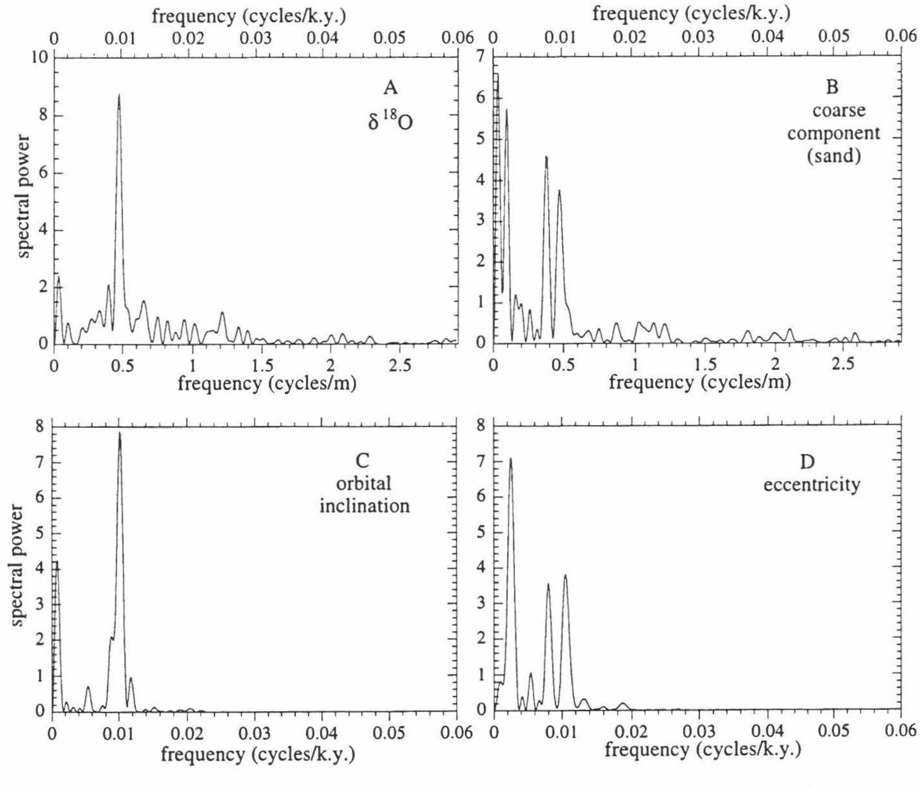

Figure 2. Spectral analysis: (A) δ^{18}O of pelagic foraminifer *G. sacculifer*; (B) coarse component; (C) orbital inclination of Earth, and (D) orbital eccentricity of Earth. Data for A and B are from Figure 1; data for C and D were calculated by Quinn et al. (1991) and transformed to invariable plane of solar system by Muller and MacDonald (1995). Note similarity between A and C and likewise between B and D.

variations in the sand fraction (which has a mean of 0.29 and standard deviation of 0.09). However, although our time scale may contain inaccuracies, it has the advantage of being *unbiased* because it is untuned, i.e., it does not assume the correctness of any orbital climate model.

NTERPRETATION OF SPECTRA

In Figure 2C we have plotted the spectrum of orbital inclination changes for the same time inerval as the data (0–908 ka). In Figure 2D we have plotted the spectrum of the eccentricity changes for the same period. From a comparison of these spectra with the δ^{18}O spectra in Figure 2A, we see that the spectrum of the δ^{18}O data s similar to that of orbital inclination, but is strikngly different from that of eccentricity; in particular, the spectral power in the vicinity of the frequency $f = 0.01$ cycles/k.y. (100 k.y. period) is narrow and unsplit. This finding confirms our prior conclusion (Muller and MacDonald, 1996), which showed a similarly narrow peak in data rom other sites (the Specmap stack and Site 607). Particularly striking in Figure 2A is the absence of the expected 125 k.y. peak (f = 0.008 cycles/k.y.) from eccentricity. This is a seious problem for theories that attribute the glacial cycle to eccentricity. None of the insolaion (i.e., Milankovitch) models summarized in he review of Imbrie et al. (1993) can account for he absence of this peak.

In contrast, the spectrum of the sand-sized component Figure 2B is very similar to that of eccentricity. The power near $f = 0.01$ cycles/k.y. s split into two peaks, and there is substantial power in the vicinity of $f = 0.0025$ (400 k.y. period).

To test whether the observed split was dependent on the particular analysis that we used, we ecalculated the spectral power by using several standard windows: Hanning, Welch, Parzen, Hamming, Bartlett, and Kaiser (see Press et al., 1993). For each window used, the split nature of he 100 k.y. peak was present, although resoluion was degraded, and the structure in the vicinty of 400 k.y. was smoothed. We also did a Blackman-Tukey analysis (Blackman and Tukey, 1958), and the split peak was also present, provided that the lag was set to ⅔ or greater. (At shorter lags, the two peaks were merged into one very broad peak. It was just such a merger in prior analyses that allowed the identification of he δ^{18}O cycle with eccentricity.)

A small peak occurs in the δ^{18}O data near 0.024 cycles/k.y. (41 k.y. period). It has a spectral power equal to approximately four times the local mean (in the range 0.02 to 0.03 cycles/k.y.), which implies a confidence level greater than 90%. This peak is predicted by the standard Miankovitch theory and is associated with variaions in the obliquity of the Earth's orbit, i.e., the ilt of the poles toward the Sun. We consider it ikely that this peak arises from the standard Milankovitch insolation mechanism. A similar peak occurs in the spectrum of the coarse component.

PATCHING

Berger et al. (1993) concluded that the recovery of core from Site 806 was incomplete and that there were missing segments. In particular, by comparing the data with data from other sites, they concluded that 75 cm of core were missing in the vicinity of the B-M boundary, and they patched in a section from the nearby Site 805. The process is not unbiased, but for the remainder of this paper, we will assume that their patching and adjustment for core expansion were done correctly. Again, we set the time scale by assuming constant sedimentation rate and setting the beginning of isotope stage 19 to 783 ka.

Spectra of the patched data with our constant sedimentation time scale are shown in Figure 3. The main features of our analysis with the unpatched data are reproduced: the single narrow peak in the δ^{18}O spectrum and the split character of the peak in the coarse component. The obliquity peak near 0.024 cycles/k.y. (41 k.y. period) has been substantially strengthened to over 10 times the local power; this is a result of the strong cycle that was patched into the missing 75 cm section. In addition, a new peak has appeared near frequency $f = 0.014$ cycles/k.y. (69 k.y. period). The occurrence of a peak with about this frequency in other data sets was first noted by MacDonald (1990). If real, it may be the orbital parameter Ω as we suggested previously (Muller and MacDonald, 1996). It could also be an artifact from nonlinear interference between the 100 k.y. peak and the strengthened 41 k.y. peak (since $\frac{1}{41} - \frac{1}{100} \approx \frac{1}{69}$). But our basic conclusion is unchanged: δ^{18}O variation is driven by inclination, while the coarse component mass fraction variation is driven by eccentricity.

BISPECTRA

Bispectral analysis provides a powerful additional method for comparing two records. Peaks in the bispectra indicate the presence of three frequencies: f_1, f_2, and $f_3 = f_1 + f_2$, in a coherent phase relationship. Such frequencies in a driving force (e.g., inclination or eccentricity) should show up in the response function (δ^{18}O or coarse component). Note that it is possible for other peaks, not present in the driving force, to be present in the climate proxy; these can be created by any nonlinear climate response. Regardless, the strong bispectral peaks in the driving force *should* be present. For further discussion of the application and interpretation of bispectra for geophysical data, see MacDonald and Muller (1994).

The bispectra for the data are shown in Figure 4, along with the bispectra of the orbital elements. These bispectra were calculated by using the patched time scale of Berger et al. (1993); however, essentially the same results are obtained when we perform the analysis with the adjusted but unpatched data of Figure 1. The only substantial difference was the absence of the peak seen in Figure 4A near $(f_1, f_2) = (0.01, 0.014)$.

Orbital inclination has one strong bispectral peak near the frequency pair $(f_1, f_2) = (0.01, 0.001)$; we marked this inclination signature with the symbol I in Figure 4C. Eccentricity has a strong bispectral peak near $(f_1, f_2) = (0.008, 0.002)$; we marked this eccentricity signature with the symbol E in Figure 4D. Note that the peak I also appears in the bispectra of δ^{18}O (Fig. 4A), confirming the linkage to orbital inclination; the peak E is absent, and this fact can be taken as additional evidence that eccentricity does not contribute to δ^{18}O. In contrast, both I and E appear in the bispectrum of the coarse component (Fig. 4B). This fact suggests that both eccentricity and orbital inclination contribute to the behavior of the coarse component signal.

If the ≈70 k.y. peak seen in δ^{18}O is a nonlinear interaction of the 100 k.y. cycle and the 41 k.y. cycle, then we might expect to see a peak in the bispectrum near $(f_1, f_2) = (0.01, 0.014)$. Indeed, just such a peak is seen in the bispectrum of the patched data (Fig. 4A), but it is not present in the bispectrum of the adjusted (but unpatched) data. This result lends support to the hypothesis that the 70 k.y. peak is an artifact of the nonlinear process of patching, rather than an indication of

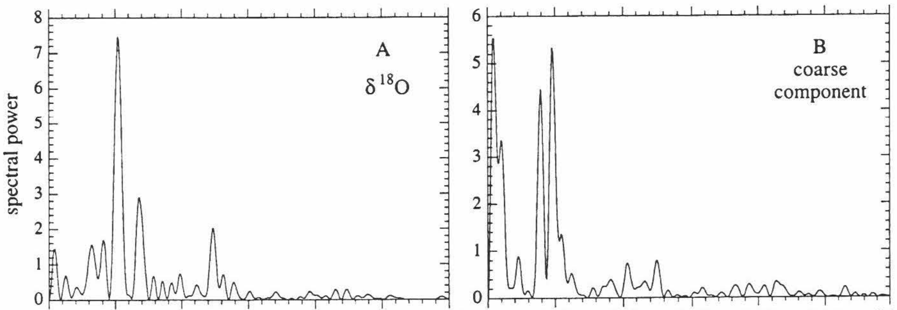

Figure 3. Spectra of data from ODP Site 806 after data were patched and adjusted by Berger et al. (1994). We assumed constant sedimentation rate and set the beginning of isotope stage 19 to an assumed Brunhes-Matuyama age of 783 ka. Basic spectral features are similar to those in Figure 2.

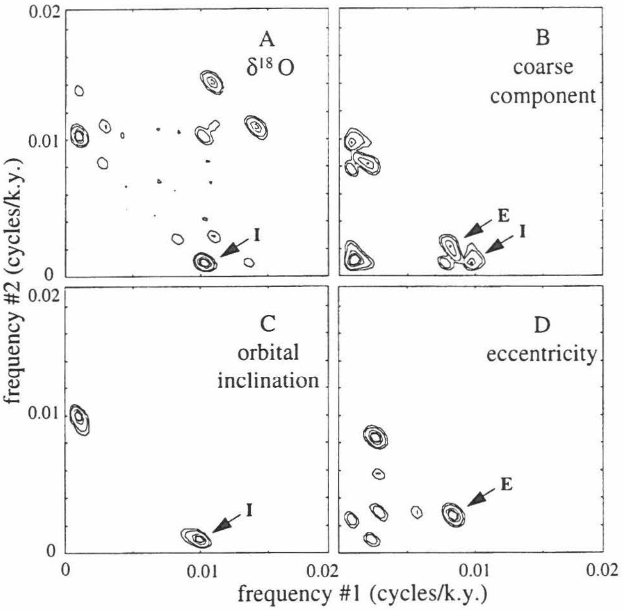

Figure 4. Bispectra: (A) $\delta^{18}O$ for site 806, (B) coarse component for site 806, (C) orbital inclination, and (D) eccentricity. Each plot is symmetric about its diagonal. The major signature of orbital inclination is the peak marked I at (f_1, f_2) = (0.01, 0.001); the major signature of eccentricity is the peak marked E at (f_1, f_2) = (0.08, 0.03). Bispectrum of $\delta^{18}O$ shows I alone; bispectrum of coarse component shows both E and I. Time scale is same as for Figure 3.

the presence of the orbital precession term Ω of Muller and MacDonald (1996).

DISCUSSION AND CONCLUSIONS

Spectral and bispectral analyses of untuned $\delta^{18}O$ data from ODP site 806 show that the 100 k.y. glacial cycle is not driven by eccentricity, as the Milankovitch theory proposes, but is related to changes in the inclination of the Earth's orbit. This finding confirms the conclusion based on minimally tuned data from Specmap and Site 607 (Muller and MacDonald, 1996).

The climate effects of eccentricity changes *are* seen in the data, but not in the proxies for global ice; rather they are seen in the sand-sized coarse fraction, which is primarily planktic foraminifera. The presence of the eccentricity signature in this signal could be explained if the foraminifera were a proxy for local climate, perhaps linked through surface-water productivity or bottom-water dissolution.

A small 41 k.y. obliquity cycle is present in the $\delta^{18}O$ data, and it may be linked to the climate through its effect on insolation, as in the classical Milankovitch theory. The 70 k.y. cycle in $\delta^{18}O$ data could be caused by orbital precession, or it could be a nonlinear artifact of the patching process.

If the 41 k.y. obliquity cycle in the $\delta^{18}O$ data comes from insolation, then why is there no eccentricity signal? One possible answer is that insolation calculations always showed the eccentricity effect to be small; in fact, the strength of the observed 100 k.y. cycle was considered an unsolved problem (see, for example, Imbrie et al., 1993). In addition, the Milankovitch response to eccentricity depends on an asymmetry in the Earth: the fact that most of the land mass is in the Northern Hemisphere. However, if glaciation is affected primarily by insolation at the poles with no asymmetry—both poles given equal weighting—then the dominant insolation response should be to obliquity. In contrast, the presence of an eccentricity response in the coarse component fraction could reflect the sensitivity of the equatorial climate to seasonal changes in the Earth-Sun separation, which do depend on eccentricity.

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REFERENCES CITED

Baksi, A., Hsu, V., McWilliams, M., and Farrar, E., 1992, $^{40}Ar/^{39}Ar$ dating of the Brunhes/Matuyama geomagnetic field reversal: Science v. 256, p. 356–357.

Berger, W. H., Bickert, T., Schmidt, H., and Wefer, G., 1993, Quaternary oxygen isotope record of pelagic foraminifers: Site 806, Ontong Java Plateau, *in* Berger, W. H., Kroenke, L. W., Mayer, L. A., et al., Proceedings of the Ocean Drilling Program, Scientific results, Volume 130: College Station, Texas, Ocean Drilling Program, p. 381–395.

Berger, W. H., Yasuda, M. K., Bickert, T., Wefer, G., and Takayama, T., 1994, Quaternary time scale for the Ontong Java Plateau: Milankovitch template for Ocean Drilling Program 806: Geology, v. 22, p. 463–467.

Berger, W. H., Bickert, T., Wefer, G., and Yasuda, M. K., 1995, Brunhes-Matuyama boundary: 790 k.y. data consistent with ODP Leg 130 oxygen isotope records based on fit to Milankovitch template: Geophysical Research Letters, v. 22, p. 1525–1528.

Blackman, R. B., and Tukey, J. W., 1958, The measurement of power spectra: New York, Dover, 190 p.

Imbrie, J., and 18 others, 1993, On the structure and origin of major glaciation cycles: 2. The 100,000-year cycle: Paleoceanography, v. 8, p. 699–735.

MacDonald, G. J., 1989, Spectral analysis of time series generated by nonlinear processes: Reviews of Geophysics, v. 27, p. 449–469.

MacDonald, G. J., 1990, Global climate change, *in* MacDonald, G., and Sertorio, L., eds., Global climate and ecosystem change: New York, Plenum Press, p. 1–95.

MacDonald, G. J., and Muller, R. A., 1994, Bispectral fingerprint identifies 100 k.y. climate cycle: Orbital inclination: Lawrence Berkeley Laboratory Report LBL-36214.

Muller, R. A., and MacDonald, G. J., 1995, Glacial cycles and orbital inclination: Nature, v. 377, p. 107–108.

Muller, R. A., and MacDonald, G. J., 1996, Spectrum of 100 kyr glacial cycle: Orbital inclination, not eccentricity: Proceedings, National Academy of Science, Conference on Carbon Dioxide and Climate, Irvine, California (in press).

Neeman, B. U., 1992, Orbital tuning of paleoclimatic records: A reassessment: Proceedings, Yale Mintz Memorial Symposium on Climate and Climate Change, Jerusalem, p. 49–52.

Olsen, P. E., and Kent, D. V., 1996, Milankovitch climate forcing in the tropics of Pangaea during the Late Triassic: Palaeogeography, Palaeoclimatology, Palaeoecology, v. 122, p. 1–26.

Press, W. H., Flannery, B., Teukolsky, S., and Vetterling, W., 1993, Numerical recipes: Cambridge, Cambridge University Press, 818 p.

Quinn, T. R., Tremaine, S., and Duncan, M., 1991, A three million year integration of the Earth's orbit: Astronomical Journal, v. 101, p. 2287–2305.

Shipboard Scientific Party, 1991, Site 806, *in* Kroenke, L. W., Berger, W. H., Janecek, T. R., et al., Proceedings of the Ocean Drilling Project, Initial reports, Volume 130, p. 291–355.

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COMMENT

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Muller and MacDonald (1997) investigated late Pleistocene oxygen sotope ($\delta^{18}O$) and coarse fraction (CF) data from an equatorial site in the western Pacific in the frequency domain. They claimed that the $\delta^{18}O$ data, which are assumed to reflect global ice volume, are dominated by a 100 ka periodicity caused by variations of the Earth's orbit with respect to the plane of the solar system. The CF data, on the other hand, show distinct spectral peaks that are assumed to be related to local Milankovitch forcing with periodicities of 95, 125, and 400 ka (eccentricity band). We would like to omment on some aspects of this study in order to show that the conclusions drawn by the authors are not compelling with respect to the data being used.

1. The autospectra are based on a Fourier transform of a truncated maximum lag of $\frac{1}{3}N$) autocovariance function. The penalty for gaining a onsistent spectral estimate is that the full length of the time series does not ontribute to the estimation. Given that the average sampling interval of the ime series is 4 ka and the number of independent data points is $N = 228$, the maximum lag corresponds to a length of 304 ka. Hence, for periods >304 ka, the results are based on less than one full cycle of the respective ignal. As a rule of thumb, periodicities with less than two full cycles should be regarded as questionable in the interpretation of estimated spectra. Although Muller and MacDonald (1997) are mainly concerned with the low requency part of the spectra, they neglect this systematic error.

2. Muller and MacDonald (1997) do not take into account the effect of olored noise on spectral estimates. Harmonic components superimposed on a red noise background—the latter being typical for climatic data (e.g., Hasselmann, 1976)—result in a mixed spectrum. In such cases, peak identiication in a spectrum is not sufficient to postulate that periodic signal components are present in a time series. Instead, harmonic analysis methods uited for mixed spectra should be used, e.g., *F*-tests based on multitaper pectral estimates (e.g., Percival and Walden, 1993) or tests based on higher order spectra (Lii and Tsou, 1992), with the test statistics corrected for the effect of zero-padding. The CF data show a clear trend in the 0–400 ka interval, which will further bias the results. It can be anticipated that this trend will produce a spectral peak with a periodicity of about 1600 ka, i.e., the leftmost peak in Figure 2B of Muller and MacDonald (1997). In order to evaluate how ed noise affects a spectrum, we generated a discrete time series $x(t_i) = \cos(2\pi f_0 t_i) + R_i$, where $f_0 = 1/100$ ka^{-1} and R_i denotes a red noise component given by the autoregressive process $R_i = 0.9\,R_{i-1} + \varepsilon_i$, with ε_i being Gaussian noise of zero mean and unit variance. In order to mimic the CF data, a linear rend was added for times <400 ka. The total length of the time series is 900 ka with a sampling interval of 4 ka (Fig. 1A). The corresponding specrum (Fig. 1B) is remarkably similar to the spectrum of the CF data given by Muller and MacDonald (1997, Fig. 2B therein). In particular, we observe a noise-induced peak slightly left of the 100 ka peak. This highlights that spectral estimates by themselves are by no means suited to test for the presence of harmonic signal components in mixed spectra. We note that the $\delta^{18}O$ data are ess affected by colored noise than the CF data (Fig. 1 in Muller and MacDonald, 1997) and that they show no obvious trend.

3. Close inspection of the CF spectrum (Fig. 2B in Muller and MacDonald, 1997) shows that the inferred 95 ka eccentricity peak has actually a period that is identical to the 100 ka peak in the $\delta^{18}O$ spectrum.

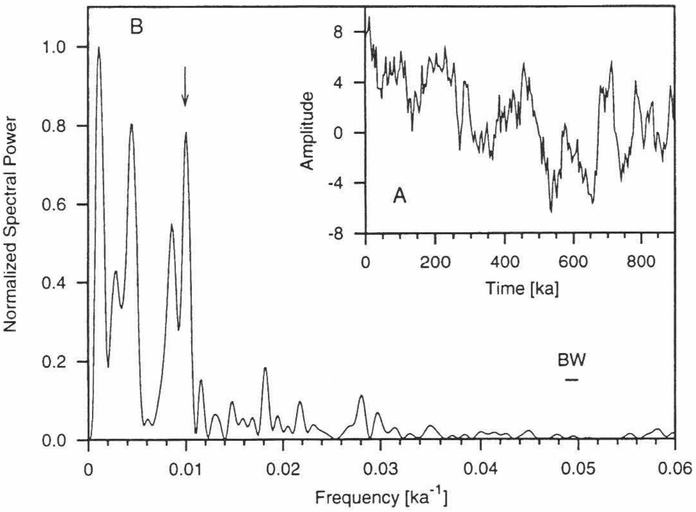

Figure 1. A: Generated time series consisting of a single periodic component (f_0 = 0.01 ka^{-1}) embedded in red noise and added linear trend. B: Spectrum of time series in A (rectangular window; BW marks 6 dB bandwidth). Note peaks at low frequencies due to noise and linear trend. Arrow marks coherent signal at f_0.

4. Based on the shape of the 100 ka peak in the $\delta^{18}O$ spectrum, Muller and MacDonald (1997, p. 4) conclude that "the signal maintains phase coherence for the entire ≈900 k.y. period." This statement implies that a harmonic 100 ka signal with non-zero amplitude is present in the entire time interval. However, a second-order spectrum cannot resolve time-varying amplitudes of coherent signals. Other methods such as wavelet analysis or evolutionary spectral analysis should be used instead. This follows also from the behavior of $\delta^{18}O$ spectrum after patching (Fig. 3A in Muller and MacDonald, 1997). The addition of a single 41 ka cycle causes a pronounced spectral peak. To conclude from this spectral peak that a 41 ka signal exists over the full time span of the time series would obviously be wrong. Furthermore, the relatively broad base of the 100 ka peak in the $\delta^{18}O$ spectrum is typical for a noncoherent but quasi-periodic signal.

5. The presence of a 41 ka peak in the $\delta^{18}O$ spectrum is considered significant and attributed to local climate forcing. However, for equatorial latitudes one would expect local forcing in the precessional band and not in the obliquity band (Berger and Pestiaux, 1984).

We thus conclude that the inferred eccentricity forcing of the CF data is most likely an artifact of the presence of colored noise in the time series. Hence, both time series show only evidence for the presence of a quasiperiodic 100 ka signal component. We agree with Muller and MacDonald (1997) that this signal is not due to direct orbital forcing. However, the results presented by them are not sufficient to exclude the possibility that the 100 ka cycle is caused by ice-bedrock interactions (e.g., Pollard, 1984) or feedbacks in the carbon cycle (Shaffer, 1990). Because the orbital inclination hypothesis fails to explain the mid-Pleistocene climate transition (e.g., Berger et al., 1993), we regard the postulated orbital inclination mechanism as cause for the 100 ka cycle to be unlikely. Finally, if orbital inclination were the pacemaker of the late Pleistocene ice ages, an age of ≈115 ka for termination II would be expected. This timing is clearly at odds with radiometric datings of corals from stage 5e.

REFERENCES CITED

Berger, A., and Pestiaux, P., 1984, Accuracy and stability of the Quaternary terrestrial insoation, *in* Berger, A., et al., eds., Milankovitch and climate, Part I: Dordrecht, Netherlands, D. Reidel, p. 83–111.

Berger, W. H., Bickert, T., Schmidt, H., and Wefer, G., 1993, Quaternary oxygen isotope record of pelagic foraminifers: Site 806, Ontong Java Plateau, *in* Berger, W. H., et al., eds., Proceedings, ODP, Scientific Results, Volume 130: College Station, Texas, Ocean Drilling Program, p. 381–395.

Hasselmann, K., 1976, Stochastic climate models: Part I. Theory: Tellus, v. 28, p. 473–485.

Muller, R. A., and MacDonald, G. J., 1997, Simultaneous presence of orbital inclination and eccentricity in proxy climate records from Ocean Drilling Program Site 806: Geology, v. 25, p. 3–6.

Lii, K.-S., and Tsou, T. H., 1992, Detecting sinusoids in non-Gaussian noise: Journal of Time Series Analysis, v. 13, p. 391–409.

Percival, D. B., and Walden, A. T., 1993, Spectral analysis for physical applications: Cambridge, United Kingdom, Cambridge University Press, 583 p.

Pollard, D., 1984, Some ice-age aspects of a calving ice-sheet model, *in* Berger, A., et al., eds., Milankovitch and climate, Part II: Dordrecht, Netherlands, D. Reidel, p. 541–564.

Shaffer, G., 1990, A non-linear climate oscillator controlled by biogeochemical cycling in the ocean: An alternative model of Quaternary ice age cycles: Climate Dynamics, v. 4, p. 127–143.

REPLY

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In their comment on our paper (Muller and MacDonald, 1997), Schulz and Mudelsee make several criticisms. We address these with the same numbers as they use:

1. Schulz and Mudelsee mistakenly assume that we calculate our Fourier transform based on a truncated (maximum lag 1/3) autocovariance function. This is a method of calculation that is commonly used in paleoclimatology and is often referred to as the "Blackman-Tukey method with 1/3 lags." They then point out weaknesses in this method. We agree with most of their criticisms of this approach—which is why we did not use it. As we stated clearly in our paper, we calculated an untapered Fourier transform on interpolated data, using zero padding to find intermediate frequencies. The narrow peaks that we observed (and which form the heart of our paper) never could have been produced by the method that Schulz and Mudelsee mistakenly assumed we used; the widths would have been three times broader (due to the 1/3 lags), and the differences between the inclination and eccentricity spectra would have been blurred out.

2. Schulz and Mudelsee state incorrectly that we do not take into account the effects of colored noise. We do take such effects into account, but because the signal-to-noise is large, the effects of noise reddening on line identification are negligible. The total noise in the vicinity of the 100 k.y. peak is dominated by two components: local noise, caused by slight chatter in the time scale, and the "red" component described by Schulz and Mudelsee. The noise level is easily determined by plotting the data on a log plot, as shown in Figure 1A. The straight line is an estimate of the red component of noise. Figure 1B shows the same data in a linear plot. The red noise has a spectral power ≈1.0 in the vicinity of the 100 k.y. peak. The 100 k.y. peak itself has spectral power 8.7 and is significant at the 1 – exp(–8.7) = 99.98% confidence level. The fact that the noise is slightly higher on the low frequency end than on the high is insignificant in deducing the width of our peak. The statement made by Schulz and Mudelsee that if *any* level of red noise is present, then peak identification is not sufficient to postulate that periodic signal components are present is inappropriate and does not take into consideration our high signal to noise levels.

To support their point, they do a spectral analysis of a noise signal, and they call attention to a spectral feature that they liken to the double peak that we find in the coarse component. However their "split feature" has negligible statistical significance; it does not stand out above the noise. Their result clearly illustrates the necessity of considering the local signal-to-noise ratio.

Schulz and Mudelsee suggest an alternative spectral approach based on multitaper analysis, a method that has received a lot of attention in recent years, and which is used in the communications industry. It is designed to suppress distant sidelobes and is most useful when searching for weak spectral peaks that are not too close to other strong peaks. But the process of tapering broadens spectral lines. When the signal-to-noise ratio is high, there is little to be gained and much to be lost. It is because of the inappropriate use in paleoclimatology of both this method and the 1/3 lagged autocorrelation method, that the narrow nature of the 100 k.y. oxygen isotope peak was previously missed.

In Figure 2, we show both a multitaper analysis and an untapered Fourier transform for a double sine wave containing periods 95 and 125 k.y. The two peaks, clearly resolved in the untapered spectrum, are not separated

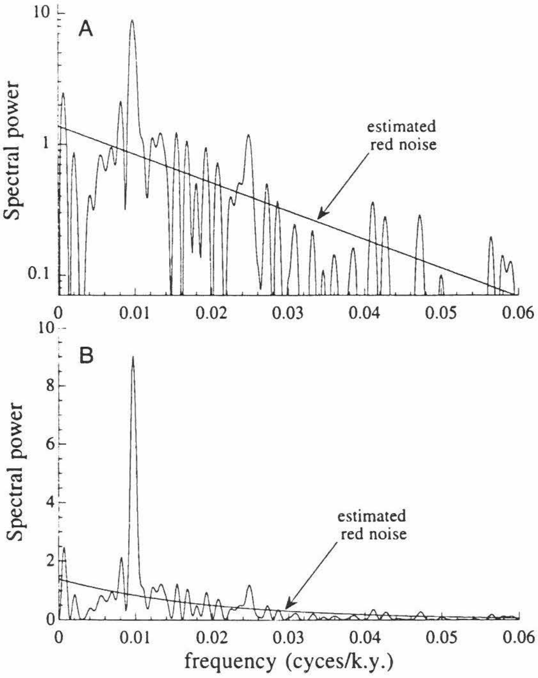

Figure 1. Spectra from Site 806, with estimates of noise. The log of the spectrum is plotted in A, and a straight-line estimate of the noise has been added. The fact that the noise peaks at low frequency is what gives it the name "red noise." In B, we plot the same data vs. spectral power. The slight variation of the noise across the frequency $f = 0.01$ peak has a negligible effect on the determinations of the peak width and statistical significance.

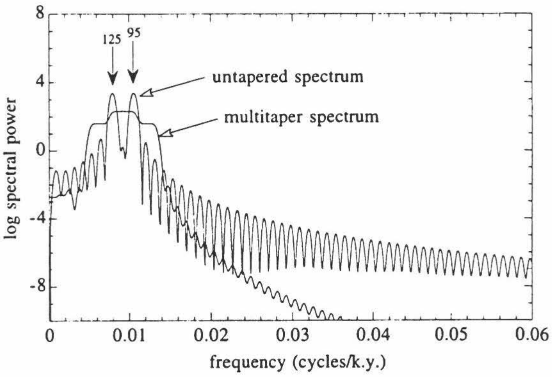

Figure 2. Two spectral analyses of the signal $y = \sin(2\pi f_1 t) + \sin(2\pi f_2 t)$ where $f_1 = 1/95$ and $f_2 = 1/125$ cycles/k.y.; these are two important frequencies present in the eccentricity variation. The multitaper spectrum suppresses the sidelobes at distant frequencies, but the untapered Fourier transform is superior at resolving the two close peaks.

the multitaper spectrum. Note that the multitaper method has much lower idelobes at frequencies distant from the strong peaks. If we were searching or very weak signals in these regions, we might prefer the multitaper ethod. Its strength is that it pulls all the power into the central peak; its disdvantage is that it does this by broadening the peak.

3. Schulz and Mudelsee state that the peaks in the oxygen data and oarse component are "identical." This ignores the statistics of the data, the esolution of the peaks, and the obviously non-Gaussian noise. With a full-idth-at-half-maximum of 10 k.y., we cannot measure the periods of the eaks with sufficient accuracy to conclude that they are identical or that they iffer by 5 k.y.

4. Schulz and Mudelsee claim that maintaining phase coherency for e entire 900 k.y. implies a harmonic signal with nonzero amplitude for the ntire period. This is not true. We make no assumption about the constancy f the amplitude. If the amplitude of a sine wave is reduced in the center of time record, then the spectral width of the peak can actually be narrowed, s long as the phase of the cycles near the end of the record is the same as the hase near the beginning.

5. Schulz and Mudelsee say that they cannot accept the presence of the 1 k.y. peak as significant, because it conflicts with their theoretical expecation. We feel that no response is necessary to this "criticism." It is worthhile to point out, however, that their theoretical expectation is based on an mplicit assumption of significant climate decoupling between the northern and southern hemispheres. If the coupling is strong, then the 23 k.y. peak, which they expect to dominate, is strongly suppressed.

The conclusions that we present in our paper have strong statistical significance and are robust to any method of spectral analysis that has sufficient resolution to observe the narrow widths of the peaks. More importantly, unlike much prior work, these conclusions do not depend on a detailed tuning of the time scale—a potentially circular process that builds into the data features of the climate model that is being tested. The oxygen isotope signal, a proxy for global ice, does not show the characteristic spectrum or bispectrum expected from the standard Milankovitch theory. The data do match the spectrum and bispectrum of our orbital inclination model (Muller and MacDonald, 1995). In contrast, the coarse component, which is likely a proxy for local climate, does show a spectrum characteristic of that expected from eccentricity variations. This implies that Milankovitch forcing does play a role in local climate, although it is inclination forcing that dominates the cycles of global ice.

REFERENCES CITED

Muller, R. A., and MacDonald, G. J., 1995, Glacial cycles and orbital inclination: Nature, v. 377, p. 107–108.

Muller, R. A., and MacDonald, G. J., 1997, Simultaneous presence of orbital inclination and eccentricity in proxy climate records from Ocean Drilling Program Site 806: Geology, v. 25, p. 3–6.