**Is There an Orbital Signal in the Polar Layered Deposits on Mars?**

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The polar layered deposits (PLD)—stratigraphic sequences of ice and dust that have accumulated to thicknesses of a few kilometers at both poles—provide the most promising record of recent climate variability on Mars, but the origin of the variability and the duration of the record remain unknown. Since the Mariner and Viking orbiters observed alternating light and dark layers exposed near the margins of Mars’ polar caps, planetary scientists have speculated that the PLD contain a record of ice and dust accumulation controlled by the insolation variations caused by changes in Mars’ orbital configuration, particularly the 120 kyr obliquity and 51 kyr precession periods (e.g., Murray et al., 1972; Cutts et al., 1976; Toon et al., 1980; Cutts and Lewis, 1982; Howard et al., 1982; Thomas et al., 1992). High-resolution images and radar soundings from subsequent missions have revealed a more complex stratigraphy, which has also been hypothesized to contain orbital features (Laskar et al., 2002; Milkovich and Head, 2005; Fishbaugh et al., 2008; Phillips et al., 2008).

A similar case is often made for paleoclimate records on Earth (e.g., Hays et al., 1976), but it is worth noting that no more than ~20% of the variability in late Pleistocene climate (as recorded in marine δ¹⁸O and δD) is linearly attributable to variations in Earth’s orbital configuration (Wunsch, 2004). A long-running debate within the terrestrial paleoclimate community concerns the extent to which Earth’s glacial variability is deterministically controlled by orbital variations (e.g., Kominz and Pisias, 1979; Wunsch, 2004). Mars is subject to larger orbital variations in insolation than Earth (Ward, 1973; Laskar et al., 2004), has a thin atmosphere and no oceans, and thus may appear to have a simpler climate system, but the potential for nonlinear climate responses is significant, particularly in the dynamics of large dust storms (Pollack et al., 1979; Toon et al., 1980; Haberle, 1986; Zurek and Martin, 1993). For Mars, as for Earth, we must weigh the null hypothesis that the record of climate variability is either unrelated to shifts in orbital configuration or is related in a sufficiently complicated way that identification of the orbital imprint is not possible.
We corrupt the insolation signal by jittering the depths and by adding noise. To add jitter, we construct a random walk, \( X_n = X_{n-1} + \delta \), where \( \delta = 0.2 \) m is the depth resolution, \( \eta \) is zero-mean Gaussian noise with unit variance, and \( \phi \) is a jitter of 0.25 m, and add \( X \) to the depths in the insolation record. The resulting unevenly spaced record is resampled at an even spacing. We then add red noise—a random signal in which longer wavelengths have larger amplitudes—to the insolation signal itself. The noise is constructed as a first-order autoregressive process with lag-1 autocorrelation and variance equal to those of the insolation record. We then compute power spectra for both the unperturbed and the jittered, noisy records using a standard periodogram approach. (For convenience we use the term “power spectra” with the understanding that the periodograms are estimates of the true power spectra.)

Figure 2 shows the results of this exercise for accumulation rates of 0.02 mm/yr, 0.2 mm/yr, and 2 mm/yr, which span the range of estimated rates. Peaks corresponding to the 51 kyr precession and 120 kyr obliquity cycles in summer solstice insolation intensity are clearly visible in the unperturbed spectra (Figs. 2A–2C), except that the record with an accumulation rate of 2 mm/yr is too short to resolve the obliquity cycle. Addition of our lower-bound jitter estimate and signal noise (Figs. 2D–2F) dramatically reduces the concentration of energy in high-frequency orbital bands and obscures the peaks in all three spectra, so that the overall spectral shape more closely resembles a noisy power-law trend than a background continuum punctuated by peaks. Thus, even in this relatively mild case—where simple signals, a conservative estimate of jitter, and moderate noise—it becomes difficult to detect an orbital signature.

We judge that an unambiguous detection requires at least two significant concentrations of spectral energy with a ratio of periods corresponding to that of orbital variations. A ratio of periods is required because there are no independent constraints on the age-depth relationship within the PLD, such that the wavelengths at which periodic signals should occur are unknown. Given that some fraction of a spectrum is, by definition, expected to exceed a given confidence level by chance, a set of spectral peaks with a diagnostic ratio of periods would also be evidence that the peaks are truly significant. The obliquity cycle is not resolved by the record with the fast accumulation rate (Fig. 2A), nor is the precession signal distinguishable from the background after jitter and noise are added (Fig. 2D). For the slow accumulation rate (Fig. 2C), the obliquity and precession frequencies are only a few times smaller than the Nyquist frequency of the image-based stratigraphy, and are therefore especially susceptible to smearing by jitter (see Huybers and Wunsch, 2004). As a result, the precession peak cannot be distinguished from the background, and the obliquity peak becomes a broad rise in power with marginal significance (Fig. 2F). Only for the intermediate accumulation rate are significant concentrations of spectral energy apparent at both the obliquity and precession bands in the noisy spectrum (Fig. 2E).

This analysis of synthetic stratigraphic records indicates that while jitter, noise, and short record duration do not categorically preclude the detection of an orbital signal, they do make it difficult. We now turn toward applying these insights to the interpretation of the actual NPLD stratigraphy.

**SPECTRAL ANALYSIS OF PLD STRATIGRAPHY**

To test for the presence of periodic signals within the PLD, we search for spectral peaks that deviate significantly from the expected shape of a noise spectrum. Using the method described in the previous section, we construct profiles of image brightness versus depth for 24 images from around the north polar cap, and compute the power spectrum for each profile. In all the spectra, power increases with wavelength until it levels off at the longest wavelengths (Fig. 3), consistent with a lag-1 autoregressive process—
The spectrum in concentrated at bed thicknesses of a few meters. Intermittent bedding sequences with variability (1998). Of the 24 wavelet spectra, 19 indicate methods described by Torrence and Compo 95% confidence level for red noise (Fig. 3).

There are, however, two deviations relative to a simple red noise spectrum: First, at intermediate wavelengths of roughly 5–10 m, the image spectra have systematically lower power than the red noise spectra; and second, most of the image spectra contain broad peaks centered at wavelengths of a few meters that exceed the 95% confidence level for red noise (Fig. 3).

The consistency among images from various parts of the north polar cap suggests that these are real features of the NPLD.

As observed in the synthetic signal analysis, narrow-band processes with short wavelengths are especially susceptible to jitter and tend to be smeared across a broad range of frequencies. To explore the stratigraphic features associated with the high-frequency variability, we calculate wavelet transforms of the image profiles using methods described by Torrence and Compo (1998). Of the 24 wavelet spectra, 19 indicate intermittent bedding sequences with variability concentrated at bed thicknesses of a few meters. The spectrum in Figure 4 is typical of those 19.

We obtain a measure of this characteristic thickness in each of the 19 images by identifying the peak in the depth-averaged wavelet spectrum that exceeds the 95% confidence level for red noise. Peaks more energetic than expected for a simple red noise background occur at wavelengths of 1–2 m where uniform bedding is visible in the image. The global wavelet spectrum below shows the average over the depth profile (blue line), with the corresponding red noise spectrum (black line), 95% confidence level (dashed line), and arrow indicating the largest exceedance of the noise spectrum.

**DISCUSSION AND CONCLUSIONS**

A fundamental limitation to interpreting the PLD climate record is the lack of an absolute chronology. The stratigraphy reconstructed and analyzed here fails to resolve this problem because no clear connection can be made with a forcing function with a known time scale. The variance in the image-based stratigraphy is largely consistent with a stochastic formation process—one that is either random, or sufficiently nonlinear that it cannot be detected using conventional spectral methods.

Nonetheless, the 1.6 m bedding could be an orbitally forced signal that is distorted by noise, stratigraphic jitter, and nonlinearities in the relationship between insolation and stratigraphy. There is some resemblance between the structures of the image spectra (such as the example in Fig. 3) and that of the jittered and noisy 20 Myr insolation spectrum (Fig. 2F). If the 1.6 m bedding formed in response to obliquity or precession forcing, it would imply accumulation rates of 0.014–0.032 mm/yr and a total formation time of roughly 30–70 Myr for the upper portion of the NPLD (unit ABB, of Tanaka et al., 2008), which has a typical thickness of 1 km. This formation time is within the upper bound of ~1 Gyr imposed by the underlying geologic units (Tanaka et al., 2008).

Alternatively, the 1.6 m bedding may have been formed by processes that are not directly related to orbital forcing, such as interannual variability in dust deposition (e.g., Haberle, 1986). We note that phenomena in Earth’s climate, such as the El Niño Southern Oscillation and Dansgaard-Oeschger events, tend to concentrate variance at a particular time scale without being directly forced by orbital variations, and can also be intermittent. If the 1.6 m beds represent time intervals much shorter than orbital periods, it is possible that the NPLD formed within the last few million years, a scenario that has been proposed on the basis of climate modeling (Levrad et al., 2007) and radar observations of the large-scale stratigraphy of the NPLD (Phillips et al., 2008).

A robust estimate of absolute age would require multiple periodic bedding signals with a ratio of wavelengths that is diagnostic of known orbital periods. If the 1.6 m bedding is an obliquity signal, for example, we might expect to find a precession peak at 0.7 m. At present, however, the 1.6 m bedding is the only significant deviation from a simple red noise continuum that is systematically observed throughout the NPLD. This result differs from that of Milkovich and Head (2005), who report that the NPLD contain a dominant wavelength of roughly 30 m, but do not identify any short-wavelength signals. They implicitly assume that the spectral background is white noise—in which average power is the same at all wavelengths—and that the wavelength band with the highest power (tens of meters) represents the largest exceedance of this background, and therefore the most periodic signal. But a white noise background is inconsistent with the PLD spectra, which invariably have more power at longer wavelengths (Fig. 3). Our analysis also differs from that of Laskar et al. (2002), who derive an age estimate for the NPLD by tuning the brightness-depth record derived from one image to match the insolation record. Tuning the age model of even a wholly stochastic record to an assumed orbital forcing will generally create spurious orbital-like variability (Huybers and Wunsch, 2004), and in the spirit of Hays et al. (1976), we suggest that the presence of an orbital
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