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A procedure for testing the significance of orbital tuning of the martian polar layered deposits

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ABSTRACT

Layered deposits of dusty ice in the martian polar caps have been hypothesized to record climate changes driven by orbitally induced variations in the distribution of incoming solar radiation. Attempts to identify such an orbital signal by tuning a stratigraphic sequence of polar layered deposits (PLDs) to match an assumed forcing introduce a risk of identifying spurious matches between unrelated records. We present an approach for evaluating the significance of matches obtained by orbital tuning, and investigate the utility of this approach for identifying orbital signals in the Mars PLDs. Using a set of simple models for ice and dust accumulation driven by insolation, we generate synthetic PLD stratigraphic sequences with nonlinear time–depth relationships. We then use a dynamic time warping algorithm to attempt to identify an orbital signal in the modeled sequences, and apply a Monte Carlo procedure to determine whether this match is significantly better than a match to a random sequence that contains no orbital signal. For simple deposition mechanisms in which dust deposition rate is constant and ice deposition rate varies linearly with insolation, we find that an orbital signal can be confidently identified if at least 10% of the accumulation time interval is preserved as strata. Addition of noise to our models raises this minimum preservation requirement, and we expect that more complex deposition functions would generally also make identification more difficult. In light of these results, we consider the prospects for identifying an orbital signal in the actual PLD stratigraphy, and conclude that this is feasible even with a strongly nonlinear relationship between stratigraphic depth and time, provided that a sufficient fraction of time is preserved in the record and that ice and dust deposition rates vary predictably with insolation. Independent age constraints from other techniques may be necessary, for example, if an insufficient amount of time is preserved in the stratigraphy.

1. Introduction

The topographic domes of the north and south polar ice caps on Mars are mostly composed of kilometers-thick layered sedimentary deposits, the polar layered deposits (PLDs), which are exposed in spiraling troughs cut into the caps (Murray et al., 1972; Cutts, 1973; Howard et al., 1982; Byrne, 2009), as shown in Fig. 1. The PLDs were initially seen in images from the Mariner 9 spacecraft (Murray et al., 1972), and were immediately inferred to be composed of atmospherically deposited dust and ice (Cutts, 1973). Since then, the PLDs have been more thoroughly characterized. Carbon dioxide ice and clathrate hydrate have been shown to be compositionally insignificant based on their effects on thermal properties (Mellon, 1996) and bulk strength (Nye et al., 2000). Water ice dominates dust volumetrically; dust volume composition has an upper limit of 2% in the north polar cap (Picardi et al., 2005) and 10% in the south polar cap (Plaut et al., 2007) according to MARSIS radar transparency data, and ~15% in the south polar cap according to gravity anomalies associated with the area (Zuber et al., 2007; Wieczorek, 2008). Concentrations far smaller than these upper bounds could produce the observed brightness differences (Cutts, 1973). MOLA topography demonstrates that the ice caps are dome-like structures 3–4 km thick (Zuber et al., 1998), with volumes of 1.14 million km^3 for the northern dome (Smith et al., 2001) and 1.6 million km^3 for the southern dome (Plaut et al., 2007). The deposits are locally overlain by seasonal carbon dioxide frost (Smith et al., 2001). Radar soundings from the SHARAD instrument (Phillips et al., 2008) have revealed that large-scale stratigraphy is similar in different parts of the northern ice cap, implying that the PLDs record regional or global climate phenomena rather than local conditions.

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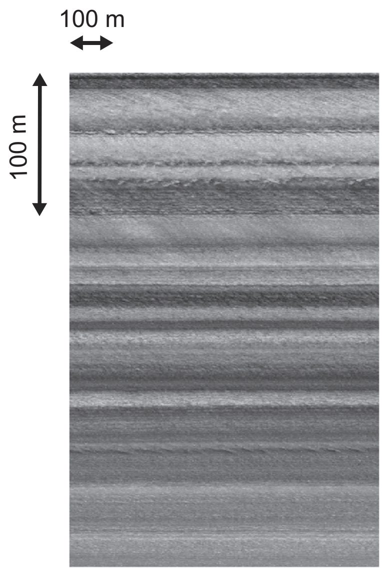

Fig. 1. Mars Orbiter Camera (MOC) Image #M0001754 of a PLD stratigraphic sequence, corrected for topography. The vertical scale corresponds to vertical depth within the PLD sequence, and the horizontal scale corresponds to distance along the outcrop.

Many authors have attempted to constrain the deposition rates of polar ice or dust (Pollack et al., 1979; Kieffer, 1990; Herkenhoff and Plaut, 2000), but these estimates span orders of magnitude. Populations of impact craters on the polar caps provide some constraints, including an estimated mean surface age of 30–100 Myr for the southern PLDs (Koutnik et al., 2002) and an estimated upper limit on the accumulation rate of 3–4 mm/yr for the northern PLDs (Banks et al., 2010). Despite these efforts, the ages of the PLDs remain poorly constrained.

It has been proposed that patterns in the thickness and brightness of these layers, which are thought to result from variable dust concentration in the ice, are controlled by changes in the distribution of solar radiation due to quasi-periodic variations in the planet's spin and orbital characteristics over time, specifically climatic precession, obliquity variation, and eccentricity variation (Murray et al., 1973; Cutts et al., 1976; Toon et al., 1980; Cutts and Lewis, 1982; Howard et al., 1982; Thomas et al., 1992; Laskar et al., 2002; Milkovich and Head, 2005; Milkovich et al., 2008; Fishbaugh et al., 2010; Hvidberg et al., 2012). In this way, the PLDs may record past martian climate.

An analogous argument is often made regarding ice cores or marine sediment cores and Earth's paleoclimate. Some of the variability in marine Pleistocene paleoclimate proxies has been convincingly linked to orbital changes (Hays et al., 1976). However, there is debate about how much of the recorded climate variability was deterministically controlled by Milankovitch cycles (Kominz and Pisias, 1979; Wunsch, 2004). In theory, the problem on Mars should be more tractable than the analogous problem on Earth. The martian atmosphere is orders of magnitude less massive than Earth's, and Mars has not had a surface ocean in the recent past, two factors that should make the martian climate system simpler than the terrestrial one. Mars also experiences larger obliquity and eccentricity variations than Earth (Ward, 1973; Touma and Wisdom, 1993; Laskar et al., 2004), which should make an orbital signal, if present, stronger and perhaps easier to detect.

Despite the likelihood of a simpler climate on Mars, detection of an orbital signal in the PLDs is not a trivial task. The relationship between time and stratigraphic depth in the PLDs is unknown, and is likely nonlinear. There are no absolute ages available for any part of the deposits. Image brightness may contain noise from image artifacts, inherent noise in the deposition rates of ice and/or dust, and an indirect relationship between visible albedo and PLD composition (Tanaka, 2005; Fishbaugh and Hvidberg, 2006; Herkenhoof et al., 2007; Levrard et al., 2007). Because of these complexities and uncertainties, detection of an orbital signal in the martian PLDs using spacecraft observations poses a considerable challenge (Perron and Huybers, 2009).

The problem of orbital signal detection has been considered almost since the PLDs were first discovered. Given the lack of an absolute chronology, most efforts to interpret the PLDs have focused on modeling or analyzing their stratigraphy. The first study to consider in detail how different PLD formation mechanisms influence the resulting stratigraphy was that of Cutts and Lewis (1982). They considered two deposition models. In their first model, material composing the major constituent of the PLDs is deposited at a constant rate, and differences between layers are caused by a minor constituent that is deposited at a constant rate only when the obliquity of the planet is below a certain threshold value. In their other model, only one type of material is deposited, but only when the obliquity is below a certain threshold value; layer boundaries correspond to periods with no deposition. Although these models are highly simplified, their work revealed the sensitivity of PLD stratigraphy to factors such as ice deposition rates and thresholds, and thus hinted at the difficulty of detecting an orbital signal. More recently, Levrard et al. (2007) used a global climate model for Mars to study ice accumulation rates and concluded that formation of PLD layers must indeed be more complex than originally modeled. Hvidberg et al. (2012) built upon the models of Cutts and Lewis with physically plausible mechanisms of ice and dust deposition, and showed that their models could generate synthetic PLD sequences consistent with some stratigraphy observed in the top 500 m of the PLDs.

Other authors have used time series analysis to search for coherent signals in the PLD stratigraphy, particularly signals that may be related to orbital forcing. Milkovich and Head (2005) analyzed spectra of brightness profiles through the north PLDs, and reported the presence of a signal with a 30 m vertical wavelength in the upper 300 m of the PLDs, which they interpreted as a signature of the approximately 51 kyr cycle of the climatic precession. They assumed a linear time–depth relationship, however, and did not evaluate the statistical significance of the signal they identified. Perron and Huybers (2009) expanded this analysis, also assuming a linear time–depth relationship on average, but allowing for local variability ("jitter") in this relationship. They also evaluated the significance of peaks in the PLD spectra with respect to a noise background. Perron and Huybers (2009) found that the PLD spectra closely resemble spectra for autocorrelated random noise, but that many stratigraphic sequences contain intermittent, quasi-periodic bedding with a vertical wavelength of 1.6 m. Subsequent studies have confirmed and refined this measurement of 1.6 m bedding through analyses of higher-resolution imagery and stereo topography (Fishbaugh et al., 2010; Limaye et al., 2012).

These applications of conventional time series analysis techniques have revealed signals within the stratigraphy, but have not been able to conclusively identify evidence of orbital forcing due to the absence of multiple periodic signals with a ratio of wavelengths that matches the expected ratio of orbital periods (Perron and Huybers, 2009). They have also been limited by the assumption of a linear time–depth relationship, a scenario that, while possible, is rare in terrestrial stratigraphic sequences (Sadler, 1981; Weedon, 2003). Thus, while the Mars polar caps do appear to record repeating regional or global climate events, the duration of these events and their relationship to orbitally forced variations in insolation remain unknown.

In studies of terrestrial paleoclimate records, it is common to address the problem of unknown time–depth relationships by