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Notes
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ABSTRACT

Over the past 25 yr, the science of stratigraphy has evolved to include time-correlative data from vastly disparate components of the Earth system. Not least of these is the global signal afforded by cyclostratigraphy, which has recorded the evolution of Earth’s astronomical (“Milankovitch”) forcing of insolation and the paleoclimate system. Fossil astronomical signals are collected from cyclic sedimentary sequences by detailed sampling and study of facies, geochemistry, mineralogy, rock magnetism, color, etc. In step with the documentation of astronomically forced paleoclimate from ever-older older geologic times, innovations in computational science have provided ever-higher high-accuracy astronomical model “targets” that can be used for time scale calibration. The Earth’s orbit is affected by motions of other planets, notably the orbital perihelia of Venus and Jupiter, which impose a dominant 405 k.y. eccentricity cycle on Earth’s orbital evolution. The large mass of Jupiter stabilizes this cycle over hundreds of millions of years. The cyclostratigraphic record of 405 k.y. cycles is therefore often used to correct chronologies affected by variable sedimentation. Earth’s shape and rotation rate are influenced by tidal dissipation and climate friction; these effects affect Earth’s precession rate through time. Thus, a record of Earth-Moon evolution is also embedded in cyclostratigraphy. The geochronologic value of cyclostratigraphy has been affirmed through intercalibration with high-precision radioisotope dating, which today has the potential to define the ages of stratigraphic horizons with 2σ uncertainties at the scale of a Precession cycle. Precession index phasing relative to that of the obliquity elucidates the seasonal nature of astronomical forcing of the paleoclimate system. Cyclostratigraphy contributes to our knowledge of planetary dynamics for times prior to the current ca. 50 Ma limit of accurate astronomical solutions, and it will guide our future understanding of solar system evolution and the evidence for chaotic diffusion. Astronomical modeling is undergoing its own revolution with development of new numerical integrators to extend accuracy further back in time. Finally, space exploration has revealed prominent sedimentary bedding and ice stratigraphy on the surface of Mars, with patterns suggestive of astronomical forcing analogous to Earth.

INTRODUCTION

With the 1941 publication of Kanon der Erdbestrahlung, Milutin Milankovitch consolidated a lifetime of study on the role of the Sun and solar system in driving climate change on Earth. This work followed on many notable predecessors who had contemplated astronomical origins of climate change, the ideas of whom were recently reviewed by Hilgen (2010) and Berger (2012). Milankovitch was the first among these creative minds to provide a complete mathematical treatment of solar radiation variations for different latitudes and seasons, an accomplishment that has stood the test of time (Fig. 1). Unfortunately, Milankovitch encountered resistance from geologists confronted with a poorly dated, fragmented terrestrial record of past climate; he died before his theory could be tested fairly with adequate evidence.

The first substantial evidence for astronomically paced climate change arose, ironically, from the buffered oceanic record. Emiliani (1955, 1966) found that biogenic marine sediment had a variable oxygen isotope history, which he attributed to variable sea-surface temperatures synchronized with the Pleistocene glaciations. Shackleton (1967) reinterpreted the Pleistocene marine oxygen isotopes as primarily an ice-volume proxy, although recent modeling suggests that the isotope signal is 50% ice volume and 50% temperature (Bintanja and van de Wal, 2008). With the advent of deep-sea drilling, evidence for an astronomical signal in marine oxygen isotopes emerged with the discovery of a multiple-period, 41 k.y. (thousand year), 19 k.y., and 23 k.y. cyclicity associated with Earth’s obliquity and precession (Hays et al., 1976; Berger, 1977). This culminated with the development of an “orbital chronology” defined for the past 780 k.y. (Imbrie et al., 1984), and astronomical models extending several million years into the past (Verneker, 1972; Bretagnon, 1974; Berger, 1976, 1978). Computer modeling studies explored the potential climatic effects of astronomically forced solar radiation, from simple energy balance models (North et al., 1983) to general circulation models (Kutzbach, 1985). After 1988, research on the astronomical theory of climate accelerated on both observational and theoretical fronts. The term “cyclostratigraphy” was coined by Fischer et al. (1988) to represent sedimentary deposits with cycles in the so-called Milankovitch band (Strasser et al., 2006). The sapropelic sequences of the Mediterranean region have become iconic examples of astronomically forced cyclostratigraphy (Fig. 2). Improvements in the sampling and analysis of cyclostratigraphy, especially as part of the Deep Sea Drilling Project (DSDP) and Ocean Drilling Program (ODP; later the International Ocean Drilling Program), led to the acquisition of continuous sequences spanning tens of millions of years at a time. Astronomical models evolved from analytical approximations to detailed, computerized numerical solutions (Laskar, 1990; Quinn et al., 1991; Laskar et al., 1993, 2004a; Varadi et al., 2003). These innovations enlarged the catalog of predicted astronomical frequencies, illuminated the role of chaotic diffusion in the solar system, and resulted in the calculation of high-accuracy astronomical solutions back to 50 Ma (Laskar et al., 2004a, 2011). Astronomical forcing signals embedded in cyclostratigraphy can be exploited as a geochronometer. This has led to a now long-standing effort to quantify astronomical signals in cyclostratigraphy and to integrate them into the global chronostratigraphic framework (Hinnov and Ogg, 2007; Pälike and Hilgen, 2008). Today, the Geologic Time Scale 2012 (Gradstein...
et al., 2012) utilizes an absolute astronomical time scale (ATS) to calibrate much of Cenozoic time, and numerous multimillion-year-long “floating” ATS intervals in the Mesozoic time scale (Hinnov and Hilgen, 2012). Inter-calibration between the ATS and high-precision geochronology to estimate and reduce error is an ongoing activity. Computer modeling of Milankovitch-forced climate change has moved forward with new applications of sophisticated atmosphere-ocean general circulation models (e.g., Ashkenazy et al., 2010; Antico et al., 2010; Merlis et al., 2013a, 2013b) and Earth system models (e.g., Gallée et al., 1991, 1992; Cane et al., 2006; Braconnot et al., 2007a, 2007b; Ganopolski and Calov, 2012; Crucifix, 2012).

This paper reviews key developments in cyclostratigraphy that have taken place over the past 25 yr. The astronomical theory of climate change gained wide acceptance during this time, and much effort has been focused on the exploration and modeling of fossilized astronomical signals. Nonetheless, basic problems continue to undercut the discipline, including separating the astronomical signal from climatic and stratigraphic noise, and understanding how the astronomical signal propagates through the climate system and into the stratigraphic record. These problems are a recurring theme in this review. The roles of astronomical and geophysical parameters in Milankovitch forcing are explained in the Astronomical Parameters and Geophysical Parameters sections, respectively. A description of the astronomically forced insolation follows, along with a review of recent innovations in understanding its effects on the climate system (Astronomically Forced Insolation and the Climate System Response section). The present status of cyclostratigraphy (Cyclostratigraphy; Fossil Astronomical Signals section) and the astronomical time scale (Astronomical Time Scale [ATS] section) are then discussed, together with developments in the practice of tuning and astrochronologic-geochronologic intercalibration. The emergence of long-period orbital modulations from multimillion-year-long cyclostratigraphic sequences containing information on planetary resonance and chaos is presented in the section on Ancient Solar System Dynamics, and the section Milankovitch Cycles on Mars reviews developments in the Milankovitch theory of Mars.

**ASTRONOMICAL PARAMETERS**

Quasi-periodic variations in Earth’s orbital and rotational parameters relative to the Sun force changes in seasonal, latitudinal, and total insolation, leading to local and global climate cycles at 10^4 to 10^6 yr time scales. There are two categories of variations, those arising from solar system dynamics (the orbital elements), and those arising additionally from Earth-Moon dynamics (Earth rotation and shape, obliquity of the ecliptic, and precession rate) (Fig. 3). The latter are discussed at length in the Geophysical Parameters section.

The astronomical parameters that affect insolation are: (1) Earth’s orbital eccentricity, which determines Earth-Sun distance, and thus total insolation; (2) Earth’s axial tilt, or obliquity of the ecliptic, which determines the angle of incidence of insolation, and thus the latitudinal distribution of insolation; and (3) the precession of Earth’s rotation axis, or precession of the equinoxes φ, which determines the timing and location of the seasons with respect to Earth’s orbit.

Modern numerical solutions (e.g., Laskar et al., 2004a) have now been calculated for hundreds of millions of years into the past and future, revealing complex modulating behavior in the astronomical parameters. Over 0–40 Ma (millions of years ago), Earth’s orbital eccentricity (Fig. 4A; Table 1) has varied between 0.00021318 and 0.066957, with major periodicities in the ~100 k.y. and 405 k.y. bands. The ~100 k.y. components are modulated in amplitude, with major components at 405 k.y., g₂-g₅, from interactions between the orbital perihelia of Venus and Jupiter, and 2.35 m.y., g₅-g₆, from interactions between the orbital perihelia of Mars and Earth, which also occur as direct eccentricity variations, especially the 405 k.y. cycle.

The obliquity variation (Fig. 4B; Table 1) has ranged between 22.5° and 24.5°, with a large-amplitude modulation with a period of 1.2 m.y., and a smaller one at 2.35 m.y. The first of these modulation terms originates from orbital inclination variations of Mars and Earth, s₁-s₅, and the second originates from g₅-g₆. The depicted obliquity model includes tidal dissipation indicating a faster rotation rate back in time, reflected in the shift to shorter periods in the spectrum for earlier time. The presently rapidly decreasing obliquity is clearly observed on Earth, with an equator-ward flight of the Tropics of Cancer and Capricorn at a rate of 14.4 m/yr (Chao, 1996).

The precession index (esinψ; Fig. 4C; Table 1) tracks the drift of the seasons and changes in Earth-Sun distance during the year. This drift is due to Earth’s precession and the precession of the orbital perihelion (“apsidal precession”). Together with the changes in orbital eccentricity, it produces a signal that is strongly modulated by the eccentricity. By convention, the angle φ (Fig. 3) refers to the position of the northern autumnal equinox with respect to the perihelion, and it presently has a value of 103°. Thus, the Earth’s rotation axis, which in a fixed reference system completes a precession cycle in 25,765 yr, returns to the same position.
relative to perihelion after only 21,000 yr; the variable orbital eccentricity additionally affects strong-amplitude modulations. The effect of precession on the measurement of climatic data is present in the 1659–1990 A.D. Central England Temperature (CET) instrument record as a phase drift in the seasonal cycle (Thomson, 1995). This phase drift, which has a slope determined by the precession constant, originates from the calendars used for the CET time scale, which assume an equinox-to-equinox ($\gamma$ to $\gamma$ in Fig. 3) timing of the year (365.2422 d). The drift indicates that the seasonal cycle in central England responds to the slightly longer, perihelion-to-perihelion (P to P in Fig. 3) timing of the year (365.25964 d).

The long-term outcome for paleoclimate change is a multiple-component variation with major periods at 24 k.y., 22 k.y., and 19 k.y. Faster rotation rates earlier in time shorten these terms while maintaining the modulation from the eccentricity. The phasing of precession-forced insolation shifts progressively through 360° during the course of the year; this is depicted for specific dates from September to March at the upper right of Figure 4C. Synonyms for the precession index are: precessional parameter, climatic precession, astroclimatic parameter, and precession-eccentricity syndrome.

The common terms “orbital forcing” or “orbital tuning” are synonymous with “astronomical forcing” and “astronomical tuning.” In this paper, the more general term “astronomical” is used to acknowledge that the precession and obliquity do not have strict orbital origins but involve geophysical phenomena, as opposed to the orbital eccentricity and inclination. Finally, the term “forcing” is distinguished from “pacing” in that the latter contemplates nonlinear climate responses to Milankovitch forcing.

**GEOPHYSICAL PARAMETERS**

Earth’s rotation and dynamical ellipticity (which together influence its moments of inertia) affect Earth’s precession rate, which in turn acts on the obliquity and precession index. Thus, a record of Earth’s geophysical evolution is embedded in cyclostratigraphy. These geophysical factors are summarized as follows.
Precession Rate, Rotation, and Ellipticity

Earth precesses in space as a consequence of its obliquity angle relative to the ecliptic of date (Fig. 3) and the gravitational pull from the Moon and Sun, expressed as the precession rate (e.g., Berger et al., 1992):

\[ k = \frac{(3/2)(\eta/\Omega)H}{[(1 - e^2)^{1/2} + (m_c m_a) \sin \omega] \left(1 - e_c^2\right)^{1/2} \left(1 - [3/2]\sin^2 I_e\right) \cos \epsilon}, \]  

(1)

where \( \eta \) is the mean motion of the Sun, \( \Omega \) is Earth’s rotation rate, \( a \) is the semimajor axis of Earth’s orbit, \( e \) is Earth’s orbital eccentricity, \( a_c \) and \( e_c \) are semimajor axis and eccentricity of the Moon’s orbit, \( I_e \) is inclination of the Moon’s orbit on the ecliptic, \( m_c \) and \( m_m \) are masses of the Moon and Sun, and \( \epsilon \) is the obliquity angle of Earth (= 23.4326° at epoch J2000). \( H \) is Earth’s dynamical ellipticity, defined as the normalized difference between Earth’s time-variable polar (C) and mean equatorial (A and B) moments of inertia:

\[ H(t) = [C(t) - (A(t) + B(t))/2]/C(t), \]  

(2)

Table 2 indicates major contributions to \( k \). The range of \( \epsilon \) is small (22.5° to 24.5°), and so a simplification can be made using a constant \( c_i \) (Brouwer and Clemence, 1961):

\[ k = c_iH/\epsilon. \]  

(3)

For measurable changes in \( k \), \( H \) is fast-varying, imposing time-variable changes on the order of 1% per 100,000 yr (Thomson, 1990; modern observations in Chao, 2006). \( \Omega \) is slow-varying, imposing deep-time changes on the order of 1% per 50 m.y. (e.g., Denis et al., 2002).

The precession index and obliquity variations (see Astronomical Parameters section) are the result of perturbations to \( k \) from planetary motions described by fundamental frequencies \( g \) and \( s \) (Table 1). Precession index modulations derive from \( g \), and thus are directly related to Earth’s orbital eccentricity; obliquity modulations are from \( s \) and other effects (Laskar et al., 2004a). The modulations can be extracted from the geological record of precession and obliquity variations. Changes in \( H \) and \( \Omega \) in \( k \) may be detected as phase aberrations in the modulations (Thomson, 1990). Comparison of observed paleovariations to models with adjustable \( H \) and \( \Omega \) is another way to estimate \( k \) (Lourens et al., 2001; see next section).

Tidal Dissipation and Earth Deceleration

Twentieth-century lunar laser ranging (Dickey et al., 1994) and historical solar eclipse observations have provided direct evidence of lunar recession and change in length-of-day (LOD), i.e., slowdown in Earth’s rotation rate, for the past 2500 yr (Stephenson, 2003). For earlier times, a handful of uncoordinated paleontological (corals, bivalves) and sedimentary (“tidal” “lilite”) data offer quantitative LOD snapshots back to 2.5 Ga (Fig. 5). The evidence, while exceedingly sparse, indicates that the change in LOD through geologic time has not been constant. This could be the result of different past continent-ocean configurations, altering tidal dissipation in the oceans; in the Precambrian, a developing inner core could have affected (lessened) deceleration (Denis et al., 2011). A third, lesser-known archive of LOD is cyclostratigraphy.

To date, four studies have assessed past \( H \) from Neogene cyclostratigraphy. Each study applied different quantitative methods to estimate \( H \); two of these studies also estimated past \( \Omega \):

**Study 1 (0–0.7 Ma)**

Thomson (1990) noticed systematic differences between the spectral lines of the SPECMAP stack (Imbrie et al., 1984) and the theoretical obliquity and precession index frequencies (Berger, 1978), suggesting that the SPECMAP signal was perturbed as a result of the repeated massive ice-sheet loading/unloading in the Northern Hemisphere. Sliding coherency and cross-phase analysis between the data and model obliquity and precession index revealed differential phasing between obliquity and precession cycles that could be explained by varying precession rate \( k \) by ±10% at 100,000 yr (glaciation-scale) time scales.

**Study 2 (0–5.3 Ma)**

Lourens et al. (1996) compared astronomical models with different values for \( H \) and \( \Omega \) to cyclostratigraphic (oxygen isotope) data from the Mediterranean Sea and Atlantic and Pacific Oceans, concluding that the best fit was to a model based on present-day values.

**Study 3 (2.4–2.9 Ma)**

Lourens et al. (2001) undertook a close statistical examination of a high-resolution Ti/Al record from the Mediterranean ODP Site 967 and deduced that significantly lower (half) than predicted combined tidal dissipation and dynamical ellipticity effects influenced the cyclostratigraphy. They also concluded that Earth’s precession had not experienced resonance (see Climate Friction and Precession Resonance subsections) over the past 5.3 m.y.

**Study 4 (0–25 Ma)**

Pälike and Shackleton (2000) showed that present-day \( H \) and tidal dissipation applied to astronomical tuning target curves for the past...
Cyclostratigraphy and revolutionizing applications

Figure 4.
25 m.y. produced a consistent fit with ODP Leg 154 (Ceara Rise) cyclostratigraphy. The results were based on interference patterns among astronomical solutions constructed with different $H$ and $\Omega$ histories over the past 25 m.y., and cyclostratigraphic data tuned to the solutions. The analysis was innovative in exploiting long-term phasing effects from hypothesized small changes in $k$.

While this evidence indicates similar bounds on Earth’s dynamical ellipticity for both the past 3 m.y. and past 25 m.y., it results in incompatible inferences about mantle viscosity (Morrow et al., 2012). The most recent 3-m.y.-long interval was dominated by repetitive glacial loading; changes in $H$ were primarily from rapid isostatic adjustments and thus imply low mantle viscosity. The 25-m.y.-long time interval in contrast would have been dominated by slowly evolving effects on $H$ from mantle convection, whereas the same estimated change in $H$ implies high mantle viscosity. This gives rise to an enigma that ultimately can only be resolved with longer and more accurately timed cyclostratigraphic records (Morrow et al., 2012).

There is evidence for shorter $\Omega$ in the past from Mesozoic cyclostratigraphy. Based on minimal 405 k.y. tuning (see Cyclostratigraphy: Fossil Astronomical Signals section), the Late Jurassic Kimmeridge Clay has a 36 k.y. obliquity cycle (Huang et al., 2010a), and the Late Permian Wujiaqi-Dalong Formations have a 34 k.y. obliquity cycle (Wu et al., 2013), which indicate 23 h and 22 h days, respectively, and which are consistent with the tidal dissipation model adopted for the La2004 astronomical solution (Laskar et al., 2004a).

### Climate Friction

Climate friction refers to glacial loading and response of the solid Earth (Levrard and Laskar, 2003). For convenience, changes in $H$ relative to an assumed reference $H_0$ over a given time slice may be defined, $\Delta H(t) = H(t) - H_0$ (Jiang and Peltier, 1996). Very small changes in $H$ (i.e., $\Delta H \approx 0.002$ in relative size) could bring precession into resonance with the $s$-$g_6$+$g_7$ Jupiter-Saturn contribution, inducing an ~0.4° decrease in mean obliquity (see also Precession Resonance section; Laskar et al., 2004a). Thomson’s (1990) $\Delta H$ estimate of ~1% for climate friction from Pleistocene ice loading should have been sufficient for this resonance to have occurred. If evidence for resonance cannot be found, which appears to be the case so far, this may signify that presently assumed Earth models are not adequate, and that a fully dynamical $H$ with mantle viscosity, core-mantle interface processes, and an active core needs to be considered (Dehant and Capitaine, 1997).

### ASTRONOMICALLY FORCED INSOLATION AND THE CLIMATE SYSTEM RESPONSE

#### Insolation Equation

The insolation equation was first formulated by Meech (1856) and is replicated here using the notation of Berger et al. (1993):

![Figure 5. Earth's length of day through geologic time. (A) The Moon raises a tidal bulge in the fluid and solid Earth, which is delayed due to friction between the ocean and crust, and within solid Earth, by an angle $\beta$, which is 0.2° for the M$_2$ solid Earth tide and ~6° for the M$_o$ ocean tide (Munk, 1997). Gravitational force from the Moon acts on the tidal bulge, producing a torque in a direction opposite from the rotation, causing Earth to decelerate. (B) Length of day over the past 2.5 b.y. based on geological data from Williams (2000). Corals, bivalves, and brachiopods secrete daily growth bands that modulate annually; fossils indicate more growth bands per year back in time. Stromatolite laminations have been interpreted similarly. Tidalites are a comparatively rare source of information and must be interpreted through application of Earth-Moon dynamical theory (e.g., Lowrie, 2007). NP is Earth’s rotation axis (“North Pole”).](gsbulletin.gsapubs.org)
The obliquity of the ecliptic ε controls solar declination together with the longitude of Earth along its orbit, \( \lambda = 0°–360° \) throughout the year:

\[
\sin \delta = \sin \lambda \sin \varepsilon. \tag{5}\]

Orbital eccentricity \( e \) determines \( \rho \), which is more exactly defined as:

\[
\rho = \frac{1 - e^2}{1 + e \cos \nu}, \tag{6}\]

where true anomaly \( \nu = \lambda - \delta \). Equations 4–6 demonstrate that insolation variations from the orbital eccentricity and precession index originate in \( \rho \), and those from the obliquity originate in \( \cos \zeta \).

Traditionally, Equation 4 has been evaluated at interannual intervals, e.g., once per 1000 yr, but this practice results in incomplete and even misleading representations of astronomically forced insolation. Today, forward modeling of high-resolution daily insolation and hypothesized climate system responses and/or transformations (e.g., rectification) can explain many puzzling paleoclimatic observations. When evaluated at very small time steps (\( \Delta t < 1 \) yr), Equation 4 shows that most insolation power is concentrated at diurnal and annual time scales; only very minor power occurs in the 10\(^4\) to 10\(^5\) yr astronomical band (Fig. 7; Huybers and Curry, 2006). On the other hand, the seasonal insolation cycle is modulated by the astronomical parameters, i.e., the annual insolation cycle is a “carrier” for the astronomical forcing terms. The modulations are complex: At the depicted 65°N latitude, the insolation maxima (close to December 21 insolation) may be drawn to the true celestial polar axis (solid line) and can be located by projecting an angle \( \theta \) above the north horizon point, to point NP (North Pole). Likewise, a parallel celestial polar axis (dashed line) may be drawn to intersect the east and west points of the horizon and a point on the meridian 90° away from NP. (B) Zooming onto point O highlights the local terrestrial horizon and sky at latitude \( \theta \). Bisecting the sky in the N-S direction is the observer’s meridian. N, S, E, and W are the north, south, east, and west points on the horizon. O is the observer on Earth’s surface, NP is celestial North Pole, and Z is zenith. The dome over the horizon is the top half of the celestial sphere. (C) The complete celestial sphere in terms of the horizon system of celestial coordinates at latitude \( \theta \). X is position of the Sun in the local sky at some instant (here depicted in the morning, i.e., ante meridian), z is distance XZ from the Sun to zenith point Z, also known as “zenith distance,” \( A \) is solar altitude (\( \pi/2 - z \)), \( \delta \) is solar declination DX, \( \alpha \) is solar azimuth, the angle of the Sun’s position from geographic north along the horizon, and H is solar hour angle measured from the meridian (midday). The Sun’s declination \( \delta \) is referenced to the celestial equator and varies between \( \pm \varepsilon \) throughout the year. Solar altitude \( A \) describes the angle of the Sun above the horizon; this quantity, over H hours of the Sun’s daily transit, determines the total daily insolation at latitude \( \theta \). At summer solstice (SS) and at \( \theta = 40°\)N, as Earth rotates over a 24 h period, the Sun rises at a point \( \alpha = 59° \) (east of north) on the horizon, traversing a small circle parallel to the celestial equator at a distance of \( \pm \delta \) at meridian transit, reaching a maximum altitude \( A = 50° + 23.5° = 73.5° \), and setting \( \alpha = 59° \) (west of north), having been above the horizon for \( \sim 15 \) h. At winter solstice (WS), the Sun rises \( \alpha = 121° \) (east of north) and sets \( \alpha = -121° \) (west of north) and is above the horizon for \( \sim 9 \) h. At spring or fall equinox, the Sun travels along the celestial equator and is above the horizon for 12 h. Adapted from Smart (1965); see also the online Rotating Sky Explorer (http://astro.unl.edu/naap/motion2/animations/ce_hc.html).
annual (seasonal) frequency (Fig. 8A). There are also spectral peaks in the obliquity band, but at a power level that is 4–5 orders of magnitude lower than the annual peak. Frequency modulations from the obliquity occur as small spectral lines spaced with obliquity frequency separations on either side of the annual peak; extremely weak lines from precession modulation are also present on the lower-frequency side of the annual peak (Fig. 8A, inset).

Climatic System Response

The geologic record indicates that astronomical band frequencies are dominant components in cyclostratigraphy, as discussed at length in the Cyclostratigraphy: Fossil Astronomical Signals section. Thus, a fundamental question involves the way in which astronomical frequencies are conveyed from the annual band across four to five decades of the climate spectrum to the astronomical band of the paleoclimate spectrum. In other words, how is the seasonal-scale insolation transmitted into the astronomical band by climate (and subsequently sedimentation [see Stratigraphic Effect section])? Huybers and Wunsch (2003) recognized that half-wave signal rectification resulting from climate sensitivity to only part of the annual insolation cycle can significantly boost the apparent effect of the astronomical forcing frequencies (Fig. 8B). The one-sided aspect of climate-recording sedimentation, together with a generally low (interannual) time resolution, further boosts the astronomical forcing terms as they are ultimately preserved in the stratigraphic record (see Stratigraphic Effect section).

Intradiurnal insolation was examined by Cerveny (1991) in terms of “elevation classes” revealing specific mixes of precession and obliquity signal power. Berger et al. (1993) redefined these as “zenith classes” with key corrections to Cerveny’s work. Localities with climate responding to insolation at specific solar altitudes alter the relative contributions of obliquity and precession in unexpected ways compared to the mean daily insolation usually assumed in astronomical forcing studies.

In sum, recognition that the astronomically forced paleoclimate record originates from insolation forcing at seasonal (and shorter) time scales has led to transformational insights about the paleoclimatic record (Huybers, 2006; Berger et al., 2010). Other hypotheses may be readily tested with similar considerations of the intra-seasonal insolation, potentially leading to breakthroughs in understanding how astronomically forced paleoclimate is generated and recorded, which today, for all intents and purposes, remains very poorly understood.

The Stratigraphic Effect

While climatic transformation of insolation forcing can amplify the astronomical frequencies, subsequent “climate recorder” processes,
Figure 8. Spectrum of the insolation. (A) Periodogram of the full insolation series (blue + red range in Fig. 7) showing high annual band power and low astronomical band power; the inset shows near-annual frequency terms induced by the precession index and obliquity. (B) Periodogram of half-wave rectification of the insolation (red range in Fig. 7), showing lower annual band power and higher astronomical band power than the full insolation periodogram (in A), with contributions from both precession index and obliquity frequency terms. Other spectral peaks in these periodograms are artifacts generated by the 0.0822 yr (30 d) sample rate. The green curve shows the effect of bioturbation mixing 822 yr of sedimentation at a time. By example, if sedimentation rate was constant at 5 cm/k.y., the bioturbation would have an ~4 cm mixing depth. Period designations for spectral peaks are as follows: $A = 1$ yr; $P_1 = 19$ k.y., $P_2 = 23$ k.y., $O_1 = 41$ k.y., $O_2 = 28$ k.y., $O_3 = 54$ k.y. Spectral density is in units of $\text{Watts/m}^2/\Delta f$, where $\Delta f = 1/T$, with $T =$ length of the time series.
such as sediment accumulation and bioturbation, impose a more dramatic effect (Herbert, 1994; Meyers et al., 2001, 2008; Weddon, 2003; Meyers and Sageman, 2004). If sediment containing an “extrinsic” (Herbert, 1994) climatic proxy, such as oxygen isotopes, accumulates at a constant rate, the stratigraphic effect will be limited to postdepositional processes, such as bioturbation and compaction. If the proxy is “intrinsic” (Herbert, 1994), for example, carbonate content, which contributes to accumulation rate, then the stratigraphic effect is more complex. Ripepe and Fischer (1991) modeled the combined effect of nonlinear accumulation and bioturbation on precession-forced carbonate cycles to demonstrate how the modulation of the precession index, namely, the eccentricity, is magnified. It is easy to envision that these processes operate at the smallest time steps considered for the insolation forcing discussed earlier (Climatic System Response subsection). Figure 8B illustrates the outcome of bioturbation continuously mixing the proxy response of the most recent 822 yr of sediment accumulating at a constant rate. Importantly, in order to obtain precession frequencies in the final recorded climate proxy signal, some form of rectification by the climate at the seasonal level is required prior to the ultimate sediment recording. Finally, signal distortion from postdepositional diagenesis, e.g., compaction and/or dissolution, mobilization, and reprecipitation of carbonate, may result in frequency emergence, amplification, displacement, and/or suppression, depending on the process causing the distortion (Westphal et al., 2004).

**CYCLOSTRATIGRAPHY: FOSSIL ASTRONOMICAL SIGNALS**

Astronomically forced paleoclimatic variations influence climate-sensitive sedimentation and are deposited as “cyclostratigraphy.” The science of collecting fossilized astronomical signals has evolved from the immensely powerful oxygen isotope record in marine carbonates, to the sampling of stratigraphic variations in lithology, carbonate, iron, organic carbon, clays, isotopes, rock magnetism, color, paleontology, trace fossils, and numerous other sedimentary parameters developed as paleoclimatic proxies. Decades of exploration and observation have dramatically improved the recovery of fossilized astronomical signals, which have been linked to cycles in temperature, aridity, glaciation, and sea level that cascade into and force the biosphere, hydrosphere, and geosphere.

Presented below are some of the many exceptional fossil astronomical signals that have been collected over the past 25 yr. These signals are a tribute to the concerted and sustained effort by the stratigraphic community to improve cyclostratigraphic data sampling and analysis techniques. It is notable that the majority of the signals were captured from drill core sequences, where stratigraphic control is tight and the geological materials are fresh. They herald that cyclostratigraphic research is well established and has the capacity to address multidisciplinary and interdisciplinary scientific problems ranging from the paleoclimatological to the astronomical.

**Cenozoic**

**Quaternary Period**

Representative global and regional Milankovitch-forced paleoclimate signals from the Quaternary Period are displayed in Figure 9. The Milankovitch revival began with deep sea drilling data (see Introduction), which expanded into a spectacular global array of highly correlated benthic marine oxygen isotope (δ18O) records of the Quaternary glaciations. Fifty-seven of these records are displayed in figure 2 of Lisiecki and Raymo (2005), who correlated, combined, and tuned these records into a “Pliocene-Pleistocene stack” in the tradition of Imbrie et al. (1984). This isotope stack shows a distinctive evolution of the Milankovitch signal as glaciation expanded in the Northern Hemisphere. From 3 Ma to 1.2 Ma, the isotope record is dominated by obliquity forcing. This is followed by a “mid-Pleistocene transition” from 1.2 Ma to 0.8 Ma to a higher-amplitude signal dominated by 100 k.y. cyclicity (Fig. 9B). As discussed below, this pattern occurs worldwide, and it is no more spectacular or apparently influential than on hominid evolution (deMenocal, 2004). Notably, the rise of 41 k.y. cyclicity associated with increased global glaciation and cooling at 3 Ma marks the branching of hominids into two lineages, one leading to Homo sapiens, and the other to the ultimately abandoned (possibly during the mid-Pleistocene transition) australopithecines.

Several hypotheses have been put forward to explain the pattern of paleoclimate change. Ruddiman (2003) envisioned summer insolation-forced glaciations with melting enhanced by greenhouse gas feedback. Raymo et al. (2006) observed that precession-forced glaciations in the northern and southern polar regions are antiphased, and thus would cancel the precession signal in ocean volume and reinforce the obliquity. Alternatively, glaciation may have responded to integrated summer insolation and obliquity which is a function of solar altitude and LOD; these oppose (cancel) one another at the precession scale, leaving an obliquity-only total summer energy to force glaciation (Huybers, 2006). The cause for the dramatic late Pleistocene 100 k.y. ice age cycles is also still debated. The timing suggests that ~100 k.y. eccentricity was involved (Imbrie et al., 1993). Since direct insolation forcing from orbital eccentricity is insignificant (Astronomically Forced Insolation and the Climate System Response section), presumably the 100 k.y. cycles would originate from the amplitude modulation inherent in precession forcing (Lisiecki, 2010; Meyers and Hinov, 2010; Imbrie et al., 2011). However, it has also been shown that modulations of the obliquity have a dominant 100 k.y. cycle with maxima/minima timings tied to Pleistocene glaciations (Liu, 1992, 1995, 1999). Another hypothesis put forward is that extratropical dust flux modulated by Earth’s orbital inclination may have been the cause (Muller and MacDonald, 1997). The role of obliquity forcing was revisited by Huybers and Wunsch (2005), who found a link between Pleistocene glacial terminations and obliquity maxima; subsequently, Huybers (2011) linked insolation maxima, i.e., both obliquity and precession, to the deglaciations. Nonlinear phase locking of the glaciations to Milankovitch forcing has also been considered (Tziperman et al., 2006), by which small frequency changes in the forcing entrain and lock the glaciation response. Dittevosen (2009) modeled the climate system with bifurcation points—forcing from stochastic noise “assisted” the mid-Pleistocene transition when the bifurcation points moved into a new configuration. Most recently, Rial et al. (2013) returned to the eccentricity hypothesis, proposing forced synchronization to explain the start of the 100 k.y. ice age cycling and the presence of frequency modulation in the isotope record.

Quaternary continental signals have transformed our understanding of Milankovitchian effects from pole to pole. In the Arctic region, Lake El’gygytgyn (“Lake E”; Melles et al., 2007, 2012) has a distinctly different signal from the global isotope stack. In the Lake E sediment record, Si/Ti tracks biogenic silica versus clastic input, and it is a proxy for primary production that has been hypothesized to be controlled mainly by temperature. A unique feature is the series of “super-interglacials” associated with marine oxygen isotope stage (MIS) interglacials, but which have exceptionally high amplitudes (Fig. 9C). These episodes of extreme Arctic warmth are mirrored by extensive deglaciation in Antarctica, indicating strong linkage between the polar regions. The 100 k.y. variation is relatively weak in the Lake El’gygytgyn proxies examined thus far, compared to the global isotope stack (compare Figs. 9B and 9C); instead, mixed precession-obliquity cycling indicative of direct insolation forcing (e.g., fig. 4 in Melles et al., 2007) is evident in the record.
Figure 9 (on this and following page). The pole-to-pole diversity of astronomically forced paleoclimate proxy time series for the Quaternary Period, adapted from Pillans and Gibbard (2012) and expanded to include additional seminal records. Numbers indicate marine isotope stage (MIS), a nomenclature that evolved with the discovery of progressively older glacial (even numbers)–interglacial (odd numbers) cycles in the marine oxygen isotope record. (A) Chronostratigraphic framework with magnetic reversals, subchrons, and excursions, based on GTS2012 (Gradstein et al., 2012). (B) Global marine benthic foraminiferal δ¹⁸O stack (Lisiecki and Raymo, 2005) appended with the late Pleistocene benthic δ¹⁸O record of Shackleton et al. (2000). (C) Lacustrine record of Si/Ti from Lake El'gygytgyn, NE Russia (Melles et al., 2012).
Figure 9 (continued). (D) Lacustrine record of biogenic silica from Lake Baikal (Prokopenko et al., 2006; Prokopenko and Khursevich, 2010). (E) Terrestrial record of loess/paleosols from the Jingbian section, Loess Plateau, China (An et al., 1990; Ding et al., 2002, 2005). (F) Dust record from offshore NW Africa, Atlantic Ocean, Ocean Drilling Program (ODP Site 659) (Tiedemann et al., 1994).
Figure 9 (continued). (G) Arboreal pollen (AP) record, Funza 1 and 2 cores, High Andes, Bogota Basin, Colombia (Torres et al., 2013). (H) Dust record from the Southern Ocean, ODP Site 1090 (Martínez-García et al., 2011). (I) Ice deuterium record from the Dome C ice core (EPICA [European Project for Ice Coring in Antarctica] community members, 2004). Neog.—Neogene; Plio.—Pliocene; Piac.—Piacenzian.
By contrast, further south and deep in the continental interior of Eurasia, dominant 100 k.y. cycles characterize the late Pleistocene biogenic silica record of Lake Baikal (Williams et al., 1997; Prokopenko et al., 2006; Prokopenko and Khursevich, 2010); in fact, the entire Quaternary Baikal record mirrors the global isotope stack (Fig. 9D). The reason for the fundamentally different paleoclimatic records for the two lakes is not yet known. Lake El’gygytgyn lies geographically north of—and further from—the known positions of the late Pleistocene ice sheets, while Lake Baikal lies southward. Still further south, in China’s Loess Plateau, continental sedimentary sequences have been linked to the global glacial-interglacial cycles. Loess accumulated during the arid glacial intervals, and paleosols developed on these deposits during intervening humid interglacials (Fig. 9E; Ding et al., 2002, 2005; An et al., 1990). The common timing of the loess-paleosol units and the global isotope stack cycles (and Lake Baikal cycles) suggests that great ice sheets intensified continental aridity and circulation northwest of the plateau (Gobi Desert region) sufficiently to produce and deliver loess to the plateau, first with the 41 k.y. glacial cycle, and then following the mid-Pleistocene transition with a 100 k.y. cyclicity. Recent provenance studies, however, suggest dust sources closer and due westward of the plateau, and variable source areas depending on paleoclimatic conditions (Pullen et al., 2014). Westward, in the Pannonian Basin (Hungary), boreholes penetrating ~500-m-thick Pleistocene fluvial sequences, dated with magnetic reversals and characterized with magnetic susceptibility (MS) and grain-size distribution (Nador et al., 2003), reveal variations with startling affinities to the marine δ18O record of ODP 677. Coarser sediments with high MS correspond to interglacials with an increased hydrologic cycle, greater flow, and basinward extension of the river system; the river system then contracts with drier, colder conditions during glacial periods, represented by finer-grained sediments with low MS.

Far to the west, at tropical Atlantic Ocean ODP Site 659, dust accumulation from northern African source areas shows a different pattern, with dominant 41 k.y. cycles throughout the Quaternary Period, and weak 100 k.y. cycles at MIS 11, MIS 13, and MIS 15 (Fig. 9F; Tiedemann et al., 1994). The low latitude of this depositional site and its dust source area suggests that precession-dominant insolation forcing should have played a role in the cycling, but this is not the case; integrated summer insolation (cf. Huybers, 2006) appears to have been at play.

In South America, the sediments of former Lake Bogota in Colombia have been studied for over 50 yr, yielding exquisite pollen records of Quaternary floristic evolution in the tropical high Andes. These records have long suffered from a lack of datable ashes or magnetostratigraphy; however, fresh efforts have been undertaken to develop credible matches of the arboreal pollen profiles with marine oxygen isotope records from the eastern Pacific and Mediterranean (Fig. 9G; Torres et al., 2013). This new tuning indicates that Lake Bogota formed at 1.47 Ma, when it deepened gradually over 200 k.y. and remained ~50 m deep for 400 k.y. The arboreal pollen record reveals a sensitive response to astronomical forcing as the upper forest line (UFL) moved up and down the surrounding mountains with response to temperature. Arboreal pollen increased during interglacials (with UFL at or above lake elevation) and decreased during glacial periods (UFL below lake elevation), with strong 100 k.y. cycling in the late Pleistocene. At 1 Ma (MIS 25), Aniba (alder) appeared from the Northern Hemisphere. At 800 ka, lake levels began to fluctuate at 100 k.y. intervals (based on aquatic taxa)—deep during glacial and shallow during interglacials. At 430 ka (MIS 11), a second Northern Hemisphere migrant, Quercus (oak) appeared. The onset of these events coincided with the major Pleistocene paleoclimatic events discussed earlier herein.

Southern Ocean paleoclimatic records from ODP Site 1090 (Martínez-Garcia et al., 2011) tell a now-familiar tale, with dust fluxes doubling across the mid-Pleistocene transition and evolving a high-amplitude 100 k.y. theme (Fig. 9H). This suggests that dust is a multifaceted climatic feedback, blocking insolation when in the atmosphere (cooling; Claquin et al., 2003), decreasing albedo when deposited on ice sheets (warming; Krinner et al., 2006), and increasing productivity with iron fertilization when deposited in the oceans (cooling; Martínez-Garcia et al., 2009). Finally, the 800-k.y.-long Dome C ice core in Antarctica (EPICA Community Members, 2004) has yielded multiple proxies of climate change drivers and responses, including deuterium, a proxy for temperature change (Fig. 9I), dust and grain size, dielectric profiling, and gas bubble analyses for N2O, CO2, and CH4 concentration, all of which covary with respect to deuterium. Significantly, the Dome C core gas data can be utilized in models for Earth system behavior elsewhere. The Greenland ice-sheet record is consistent with that in Antarctica, but it covers only 0 to ca. 100 ka, although with a greatly expanded resolution.

Neogene Period

By the end of the 1990s, magnetostratigraphy had been measured and matched in detail to astronomical models back into the Miocene Epoch (Hilgen, 1991a, 1991b; Hilgen et al., 1995, 1997, 1999; Lourens et al., 1996; Houben et al., 2007; Hüsing et al., 2007, 2009). Most of these studies centered on the sapropelic marine sequences that characterize Mediterranean stratigraphy through the Miocene–Pliocene (photo in Fig. 2), and today form the basis for much of the Neogene ATS (Lourens et al., 2004; Hilgen et al., 2012). An example of Miocene cyclostratigraphy fitted to the astronomical parameters is shown in Figure 10A.

Paleogene Period

Drilling progressively deeper into the Cenozoic marine record has continued to yield an exquisitely detailed oxygen and carbon stable isotope record (Zachos et al., 2001, 2008). Further back in time, ice volume and temperature contributed variably to the marine oxygen isotope record, and global sea level was significantly higher than in the Pleistocene (Miller et al., 2005; De Boer et al., 2010). An exceptional stable isotope record from the equatorial benthic Pacific Ocean was collected at ODP Site 1218, spanning the entire Oligocene Epoch (Fig. 10B; Pälike et al., 2006). Marine carbon isotopes are a proxy for oceanic productivity. This record has a large excursion to positive values at the well-known Oi-1 glaciation at 33.5 Ma, just after the Eocene-Oligocene transition marking the glaciation of Antarctica. A second major glaciation, Mi-1 at 23 Ma, marks the Oligocene-Miocene transition. Strong 405 k.y. cycles are present throughout the record; within these are the variations associated with the ~100 k.y. eccentricity, obliquity, and precession (fig. 2 in Pälike et al., 2006). The enhanced low-frequency forcing, i.e., the eccentricity frequencies, especially the 405 k.y. cycle, is attributed to long residence times of carbon in the ocean.

The Eocene Epoch was marked by global warming and evidence for high atmospheric CO2, on the order of 1000–3000 ppmv (2.5–7.5 times present-day level) (e.g., fig. 2 in Zachos et al., 2008). Significant polar ice was not yet present; the Antarctic ice sheet formed during Oi-1, with the sharp excursion to heavier oxygen in the δ18O record (Pälike et al., 2006). During the past decade, the Eocene has been a research focus of the paleoclimatology community; multiple ODP sites have drilled through Eocene ocean sediment in the Atlantic and Pacific Oceans. Many of these cores were drilled at the same time as the advent and development of high-resolution X-ray fluorescence (XRF) core scanning technologies (Richter et al., 2006). Some of the cores that were scanned produced remarkable records of iron concentration, reflecting carbonate cyclicity (which dilutes Fe concentration) with strong Milankovitch frequencies (e.g., Westerhold et al., 2007).
Figure 10. Notable Neogene and Paleogene cyclostratigraphic sequences. (A) The Miocene sapropels of Monte Gilbiscemi, Italy (see photo in Fig. 2; Hilgen et al., 1995). The sapropels (bottom) are phased with maxima of 65°N summer half-year (equinox-to-equinox) insolation (top curve), following sapropel astrochronology for the last 0.5 m.y. (Lourens et al., 2004). Other astronomical parameters are also shown (405 k.y., ~100 k.y. eccentricity, and the precession index). The depicted astronomical model is La90(1,1) (fig. 4 in Hilgen et al., 1999). (B) Astronomically tuned Oligocene δ¹³C record from benthic foraminifera from Pacific Ocean Ocean Drilling Program (ODP) Site 1218 (Pälike et al., 2006) from data provided by Zachos et al. (2008). The vertical red arrows indicate 405 k.y. cycles. Mi-1—First Miocene glaciation event; Oi-1—First Oligocene glaciation event. (C) 405 k.y. eccentricity-tuned Eocene-Paleocene iron (Fe) concentration series, Atlantic Ocean Walvis Ridge ODP Sites 1258 and 1262 (Westerhold et al., 2012). From the top: La2011 eccentricity with 405 k.y. and ~2.4 m.y. components shown; middle: amplitude envelopes of the ~100 k.y. band of the astronomically tuned Fe-concentration series; bottom: astronomically tuned Fe-concentration series from the ODP sites; note that the Fe concentrations at ODP Site 1262 are much higher, and the Fe series is shown in log scale. AM—amplitude modulation; ELPE—Early Late Paleocene Event; PETM—Paleocene-Eocene thermal maximum; ELMO—Eocene Layer of Mysterious Origin.
Two of these Fe records from Walvis Ridge have been stitched into a 13-m.y.-long series spanning the Eocene-Paleocene transition (Fig. 10C; Westerhold et al., 2012). This composite Fe series was tuned to 405 k.y. cycles, and then the 95 k.y. band was analyzed for amplitude modulations to seek evidence for g4-g3. The recovered modulations have minima that best fit the La2010d eccentricity model (Laskar et al., 2011), as shown.

**Mesozoic**

As might be expected, the Cretaceous Period is currently the widest explored interval of Mesozoic cyclostratigraphy. Already in the 1800s, Cretaceous cyclostratigraphy of the U.S. western interior was the subject of speculation about the potential role of cyclic sedimentation in time scale development (Gilbert, 1895). Today, these same formations, with their intercalations of datable bentonites, lead the way in modern astrochronologic-geochronologic intercalibration (Sageman et al., 2006; Meyers et al., 2012; see Astrochronologic-Radioisotopic Intercalibration section). Fischer et al. (2009) summarized how the Mediterranean region has provided the leading evidence for astronomical forcing of Cretaceous cyclostratigraphy, from the >30-m.y.-long carbonate-rich deep-sea sedimentary cycling archived in the Italian Umbria-Marche region to the uppermost Cretaceous-Paleogene boundary sequence at Zumaia, Spain. Recently, Chinese researchers have discovered astronomical signals in the continental deposits of the Songliao Basin (e.g., Wu et al., 2012).

Research on Jurassic cyclostratigraphy has likewise been extremely active, with the discovery and characterization of astronomical signals through much of the period (summary in Hinov and Hilgen, 2012). The developing focus on the oceanic anoxic events of the Early Jurassic has come to rely on the high-resolution astrochronology offered by cyclostratigraphy (e.g., the early Toarcian oceanic anoxic event; Jenkyns, 1988; Hesselbo et al., 2000, 2007; Kemp et al., 2005, 2011; Suan et al., 2008).

Multi-million-year-long cyclostratigraphic successions from the Mesozoic have set the standard for future cyclostratigraphic research. Several successions provide records of continuous astronomical signals that are more than 20 m.y. long. Among them is the Aptian-Albian Piombico Scisti a Fucoidi Tethyan sequence (Fig. 11A; Herbert et al., 1995; Grippo et al., 2004; Huang et al., 2010a). This is a 70 m, 25.7-m.y.-long sequence of pelagic carbonate productivity cycles that was deposited in an isolated deep-sea environment far from slope and shelf environments. Consequently, the accumulation rate was very slow, averaging 5 mm/k.y. (postcompactional), originating from an ocean surface (mostly carbonate) productivity flux. Thus, the precession

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**Figure 11.** Excerpts of proxy series from continuous Mesozoic cyclostratigraphic sequences spanning more than 20 m.y. with exquisite Milankovitch cycles. Labels: p—precession cycle; o—obliquity cycle, e—100 k.y. eccentricity cycle. (A) Grayscale scan of the pelagic marine Aptian-Albian Scisti a Fucoidi (Grippo et al., 2004; Huang et al., 2010a); shown are 405 k.y. cycles 12 and 13 from the lower “Amadeus Segment” in the *Ticinella praeticinensis* zone. (B) 6π multitaper (MTM) power spectrum of the 23.946-m.y.-long, 405 k.y. tuned grayscale scan showing strong Milankovitch periodicities. (C) Depth rank series from the cored continental lacustrine Late Triassic Newark Group (Olsen et al., 1996, 2011); shown are 405 k.y. cycles 55 and 56 in the Lockatong Formation. Depth ranks indicate facies as follows (“exposed” to “deep lake”): 0—intense breccia fabric; 1—breccia fabric; 2—mud-cracked mudstone; 3—thin-bedded mudstone; 4—finely laminated mudstone; 5—microlaminated mudstone (Olsen, 2010). The entire rank series has been tuned to the 405 k.y. eccentricity cycle. (D) 6π multitaper power spectrum of the 21.12-m.y.-long, 405 k.y. tuned Newark depth rank series showing strong Milankovitch periodicities.
cycles are a mere 8–10 cm thick. The spectrum of the series tuned to successive 405 k.y. cycles has strong eccentricity terms (Fig. 11B); precession is dispersed with low power, having not been fully corrected by tuning to 405 k.y., i.e., every 2 m interval (“minimal tuning”; see Astronomical Tuning subsection). There is also an obliquity term, which most likely shows splitting and dispersion from uncorrected accumulation rates.

The Carnian–Hettangian Pangean sequence from the Newark Basin Coring Project represents 32 m.y. in 6700 m (Fig. 11C; Olsen et al., 1996, 2011). These lacustrine deposits contain strong precession-scale (“Van Houten”) shallow-upward lithofacies cycles linked to wetting-drying climate cycles. Each precession cycle is on the order of 5 m thick and strongly modulated by eccentricity. The power spectrum (Fig. 11D) of the 405 k.y. tuned, depth-ranked lithofacies series shows a strong and well-defined eccentricity spectrum. As in the Piobibco spectrum, the precession cycles are prominent, although in the spectrum they appear diffuse, likely due to uncorrected accumulation rates. Unlike the Piobibco core, there is no obliquity term in the Newark series.

These are but two of an increasing number of exceptionally long cyclostratigraphic signals that have been recovered from Mesozoic sequences. For example, other extended signals from the Cretaceous include the following: Campanian–Maastrichtian (Husson et al., 2011; Batenburg et al., 2012; Thibault et al., 2012); Coniacian–Santonian (Locklair and Sageman, 2008); and Cenomanian–Santonian (Sprovieri et al., 2013). Researchers are also now attempting to correlate Mesozoic cyclostratigraphy globally, as has been done for the Quaternary (as in Fig. 9). For example, the ~100 k.y. cycles in the Selli level of the Piobibco core have been correlated to the Cismon core (Huang et al., 2010a). The 405 k.y. cycles of the Middle and Upper Alban Piobibco core have been correlated to 405 k.y. cycles in the Marnes Bleues (Gale et al., 2011), in the process, an ~2.4 m.y. hiatus was discovered at the latter locality. The cyclicity of the Late Triassic Mercia Mudstone Group (UK) has been correlated to the Newark series (Kemp and Coe, 2007). There is also a possible correlation at the 405 k.y. scale between the Newark series and the carbonate platform cycles of the Italian Dolomia Principale and Dachstein Limestone (Cozzi et al., 2005; Cozzi and Hinnov, 2012).

**Paleozoic**

Paleozoic cyclostratigraphy represents the next great “frontier” in the study of astronomical forcing. Marine phytoplankton evolved later, and so the stratigraphic archives occur preferentially (although not exclusively) in shallow marine depositional systems. Spectacular examples of Milankovitch-scale cycles have been found in long-lived lacustrine environments (Yang et al., 2010). The late Paleozoic, the era of the greatest Phanerozoic ice age, has stratigraphic evidence of large, global sea-level oscillations from Late Devonian to Early Permian time. The iconic Carboniferous cyclothemss record dozens of marine transgressions and regressions in North America, Europe, and Asia—seemingly anywhere in the field from the south Gondwanan ice sheets. While Paleozoic cyclostratigraphy is common, its connection to Milankovitch forcing remains for the most part unconfirmed and speculative. However, the status quo is changing rapidly, as summarized in the following representative examples.

Milankovitch cycles from the Late Permian (Lopingian Epoch) strata in China have now been calibrated to new, high-precision geochronology from in situ ashes (Wu et al., 2013). The strata display strong 405 k.y. cyclicity, which conform to the radiostoppe dating and represent a significant step in defining the Paleozoic ATS. In the American Southwest, the Ochoan (lowermost Lopingian) Castle Formation has the broadest-band record of paleoclimate of any geologic age, from annual scale to eccentricity scale, with a continuous sequence of more than 200,000 evaporitic anhydrite-carbonate varves (Anderson, 2011). The Pennsylvanian cyclothemss of North America have long been thought to represent 400 k.y. scale cycling (Heckel, 1986, 2008). Radiostotope dating in the Donets Basin, Ukraine, supports this timing, together with correlation of cyclothemss within the Donets Basin and to the North American cyclothemss (Davydov et al., 2010; Schmitz and Davydov, 2012; Martin et al., 2012; Eros et al., 2012). Detailed facies analysis differentiated internal ~100 k.y. and 20 k.y. scale cycling within a Kansas-type cyclothem in the midcontinent United States (Algeo and Heckel, 2008), and stable isotope analysis provides evidence for ice-volume oscillations at least as large as the Pleistocene ice ages (Joachimski et al., 2006).

For the Late Devonian, 100 k.y. scale cycles have been described in China (Chen and Tucker, 2003; Gong et al., 2005), and 400 k.y. scale cycles have been described in the Appalachian Basin (Algeo et al., 2006) and in basinal sequences of western North America and Poland (De Vleeschouwer et al., 2012, 2013), suggesting that a three-way intercontinental cycle correlation (in the manner of the correlation being undertaken for the Carboniferous) may be possible in the future.

As one might expect, Milankovitch forcing has yet to be forcefully demonstrated for early Paleozoic cyclostratigraphy. This is due to a combination of factors: no high-precision geochronology, incomplete biostratigraphy, no magnetic reversal stratigraphy, and lack of confidence in models of the astronomical parameters. However, 20 yr ago, the emerging science of sequence stratigraphy spawned an enormous amount of research on cyclic sedimentary sequences, much of it in early Paleozoic shallow marine carbonate. The Silurian Period is relatively brief (duration 24.6 m.y.), with eight (possibly nine) global sea-level cycles; the oldest three (Llandoveryan) are associated with tectonites (Calner, 2008; Johnson, 2010). Small shallow-upward sedimentary cycles occur within this framework (e.g., Nestor et al., 2001, 2003), but none has been studied rigorously for evidence of Milankovitch-forced deposition. The Ordovician has fared somewhat better in terms of measuring and identifying high-frequency sedimentary cycles (Kim and Lee, 1998; Gong and Droser, 2001; Rodionov et al., 2003; Long, 2007) and their organization into third-order sequences (Goldhammer et al., 1993; Kwon et al., 2006), but all suffer from lack of geochronologic control. The thick Cambrian cyclic carbonate banks around the world likewise show tantalizing evidence for Milankovitch-scale forcing (e.g., Bond et al., 1993; Osleger, 1995; Read, 1995; Bazykin and Hinnov, 2002; and many others, e.g., in Morocco and China), but all lack sufficient independent time control. Among the problems presented by these early Paleozoic sequences is the puzzling absence of observations of candidate 405 k.y. cycles by the studies. However, it should be acknowledged that most of the work was undertaken without this particular cycle in mind. Moreover, as it is becoming evident that many so-called third-order cycles in Mesozoic cyclostratigraphy are actually 405 k.y. cycles (e.g., Strasser et al., 2000; Boullia et al., 2011; see Mesozoic subsection), it will likely be necessary to revisit these sections, and to examine new ones with “fresh eyes,” and with geochronology.

**Precambrian**

The values of Earth’s astronomical parameters during the Precambrian are highly uncertain, but attempts have been made to constrain the dominant periods back to 2500 Ma (Berger et al., 1989; Berger and Loutre, 1994). We know that tidal dissipation affected the LOD (Fig. 5), which shortens the obliquity and precession cycles progressively back through time (Berger et al., 1989; Ito et al., 1993; Berger and Loutre, 1994). We also know that chaotic diffusion affected the planetary orbits, but the precise outcomes are not—and never will be—known. Will the ~100 k.y. eccentricity persist throughout the...
Precambrian? What about the 405 k.y. cycle? There is a potentially powerful gauge in Precambrian cyclostratigraphy.

The cyclic cap carbonates of the Neoproterozoic “snowball” Earths (e.g., Hoffman and Schrag, 2002) could be examined for Milankovitch forcing. Also, there is the spectacular 3.3-km-thick Wumishan cyclothem sequence of Mesoproterozoic age (dated 1.21–1.31 Ga) (Mei et al., 2001), with 626 peritidal cycles ranging from 0.6 m to 14.5 m in thickness (average 4.49 m), each representing 160 k.y., if the cycles are periodic, showing strong 4:1 bundling suggestive of a 400 k.y. modulator. The Paleoproterozoic (1.9 Ga) Rocknest carbonate platform sequence (Grotzinger, 1986) has 160 shallowing-upward cycles that, while measured in detail, have yet to be examined for a Milankovitch signal.

The Paleoproterozoic (2.5 Ga) Brockman Formation consists of banded iron formation, notably the Dales Gorge Member, which is cyclic at multiple scales (Trendall and Blockley, 1968; Simonson and Hassler, 1996; Pickard et al., 2004). Despite the strong cyclicity, and U-Pb dating (Trendall et al., 2004) indicating a 30 m.y. duration for this banded iron formation, thus far only one study has evaluated Milankovitch-band cyclicity, showing evidence for 405 k.y. and ~100 k.y. scale cycles, and shorter precession and obliquity predicted for Archean time (Franco and Hinov, 2008; Sanchez, 2011).

The oldest formation yet studied for cyclostratigraphy is a sequence of 74 shallowing-upward carbonate cycles from the Archean (2.65 Ga) Cheshire Formation, Zimbabwe (Hofmann et al., 2004), which researchers found was consistent with precession forcing with an ~11.6 k.y. mean period, bundled into ~100 k.y. eccentricity with a 10:1 ratio.

ASTRONOMICAL TIME SCALE

Radioisotope dating is the principal source of absolute time for geology, derived from a sparse stratigraphic distribution of volcanic ash beds. The hard-won precision and accuracy of the dating is all but lost in the intervening intervals. Astrochronology supplied from cyclostratigraphy restores, validates, and even enhances the accuracy and precision within these ash-poor intervals. For this reason, astrochronology has become an important tool in the geosciences, known as the astronomical time scale (ATS). As with other geochronologic tools, the ATS will require frequent updating, checking, adjusting, and extension as new data sets and methodologic improvements arise. The recently published The Geologic Time Scale 2012 (GTS2012; Gradstein et al., 2012) includes cyclostratigraphy for the past 250 m.y. to enable scaling of events (durations of biozones, magnetic reversals, relative age spans between biostratigraphic datums, etc.) and ultra-high-resolution correlations. An independently derived ATS has been developed in parallel to GTS2012 by geologists working in the Middle East, in a compilation known as the “Arabian orbital stratigraphy” (Al-Husseini and Matthews, 2005, 2010a, 2010b; Matthews and Al-Husseini, 2010; Al-Husseini, 2013).

Cyclostratigraphy resolves geologic time at the scale of individual cycles, for example, the individual precession cycles depicted in Figure 11. This allows the construction of high-resolution “floating” astrochronologies (see also “Anchored” versus “Floating” Astrochronology subsection). The challenge is to confirm the astronomical origin of the stratigraphic oscillations and then assign an absolute age to each cycle (precession, obliquity, or eccentricity) with an uncertainty that is less than the cycle itself. The ultimate goal would be to achieve precession-scale astrochronologies throughout the Phanerozoic and beyond. For the Cenozoic and latest Mesozoic, it appears as though success may be at hand: Recently improved radioisotope dating with precession to eccentricity-scale precision holds the potential to determine the time and possibly even the phasing of a single stratigraphic cycle with respect to an astronomical model (see Astrochronologic-Radioisotopic Intercalibration subsection).

Astronomical Tuning

Nineteenth-century geologists recognized that astronomical cycles recorded in a stratigraphic sequence could provide the means by which to assign a time scale to the sequence (review in Hilgen, 2010). As a case in point, Milankovitch (1941) made age predictions for the European Würm, Riss, Mindel, and Günz ice ages (Fig. 1), which while ultimately proven inaccurate (the ice ages are paced at 100 k.y. intervals), brought to bear the transformative power of astronomical tuning as it is used today. Astronomical tuning can be subjective and render interpretations vulnerable to circular reasoning. However, astronomical tuning is now undergoing a revolution with the development of statistically based objective techniques aimed to reduce circularity. Both approaches are summarized next.

The Proviso Time Scale

The “raw” cyclostratigraphic signal is reported spatially with respect to stratigraphic height or core depth. An initial, independent time scale is highly desirable to judge the basic timing of events recorded in the stratigraphy. The proviso time scale is based on radioisotope dating, correlated biostratigraphy, chronostratigraphy and magnetic reversals. However, this information is often unavailable or only vaguely defined for a given stratigraphic section. For example, both the Piobbico and Newark series have poorly defined initial time scales (see Mesozoic subsection of Cyclostratigraphy: Fossil Astronomical Signals section). A closely related challenge is a priori knowledge of an astronomical signal in the stratigraphic sequence, including the climatological and depositional mechanisms responsible for its expression. The Piobbico and Newark series have vague initial time scales, but the visual evidence for a highly organized signal with Milankovitchian patterns is compelling (Fig. 11). Conversely, the proviso time scale can aid in the discovery of the astronomical signal. For example, the Sr/Ti record at Lake El’gygytgyn (Fig. 9C), once calibrated by magnetic reversals, was found to be consistent with summer insolation (Melles et al., 2007).

Classical Astronomical Tuning

Visual astronomical tuning was developed as soon as Milankovitch theory was shown to be a viable paradigm (Hays et al., 1976). It literally entails visual matching of stratigraphic data to an astronomical “target” time model. To facilitate the correlation, band-pass filtering can (or should be) be used to isolate putative Milankovitch terms (e.g., Imbrie et al., 1984). Originally, the procedure was carried out at the drafting table, with graphical selection of correlation points and time-depth conversion for the stratigraphic data, sometimes carried out iteratively. Today, this can be done in Analyseries (Paillard et al., 1996) by selecting an astronomical target file (conveniently calculated in the application) and a stratigraphic data file (read into the application), and using the “Linage” function to visualize and correlate the two together with selections made with a mouse. Mathematical techniques have also been developed to ensure the best statistical fit between data and astronomical time model (“target”), e.g., linear inversion (Martinson et al., 1982), varimax norm demodulation (Schiffelbein and Dorman, 1986), a minimal cost function method (Brügge mann, 1992), dynamic optimization (Yu and Ding, 1998), and dynamic programming (Listiecki and Lisiecki, 2002). Insonation curves have become very popular tuning targets, forming the basis, for example, for the time scales of most of the Quaternary records in Figure 9. This practice however, has engendered much skepticism over the years: Maximizing correlation between data and target can be interpreted in terms of goodness of fit statistics and little else. That is, the astronomical “target” is generally assumed to be correct, without independent statistical assessment of whether it is actually appropriate.
An alternative approach is to tune data to a single astronomical frequency and assess the success or failure of the tuning to realign other astronomical terms. This procedure is known as “minimal tuning” (Muller and MacDonald, 2000). For example, the Pleistocene Lake Baikal chronology (Fig. 9D) is based on minimal tuning of small-scale biogenic silica cycles to the precession index, which sharpened and triples spectral power at the obliquity frequency (fig. 8 in Prokopenko et al., 2006). Tuning intermediate-scale total organic carbon (TOC) cycles of the Jurassic Kimmeridge Clay Formation to a 1/36 (k.y.) obliquity frequency results in estimated sedimentation rates with a strong eccentricity signature (fig. 7 in Huang et al., 2010b).

Kodama et al. (2010) tuned Eocene rock magnetic data to La2004 eccentricity, focusing obliquity and precession index spectral terms. For the Mesozoic, minimal tuning is the only option: The 405 k.y. eccentricity cycle is the only reliable time-domain astronomical signal prior to ca. 50 Ma (Laskar et al., 2004a, 2011). Other approaches are becoming available that rely on frequency-domain astronomical targets (see following Statistical Astronomical Tuning subsection). To date, the 405 k.y. “metronome” has been used to calibrate geologic time for significant portions of the Mesozoic, and the uppermost Paleozoic (Permian), and routinely focuses higher-frequency (100 k.y. scale) eccentricity, obliquity, and precession index signals (e.g., the Cretaceous Piobbico series and Triassic Newark series; Fig. 11).

### Statistical Astronomical Tuning

A new class of tuning procedures addresses the time scale problem with statistical modeling. The “average spectral misfit” test (Meyers and Sageman, 2007; Meyers, 2008; Meyers et al., 2012) evaluates the fit of a stratigraphic data spectrum to an astronomical target spectrum while comprehensively evaluating a range of plausible sedimentation rates. Importantly, the theoretical target spectrum only requires knowledge of the dominant periods (e.g., Berger et al., 1992), not their phases or amplitudes (as is required with the time-domain targets discussed previously in Classical Astronomical Tuning subsection). The “average spectral misfit” between data and target for each modeled sedimentation rate is calculated, and a Monte Carlo simulation of a large number of randomized spectra with the same resolution as the stratigraphic spectrum is used to test the null hypothesis of “no astronomical influence.” A similar method was developed by Malinverno et al. (2010), in which a “Bayesian Monte Carlo” approach is used to search for the sedimentation rate that maximizes spectral power at the astronomical frequencies.

These methods provide statistics on the tested sedimentation rates and allow for failure, i.e., no unique astrochronology. Both methods preserve the original phasing of the data, a requirement for interpretation of insolation forcing, and for evaluating lags of astronomical-forced proxies with respect to a model.

Depth-derived time scale modeling is another innovation for Pleistocene stratigraphy (Huybers and Wunsch, 2004; Huybers, 2007), and it has also been applied in deep time (Aswasereelert et al., 2013). The technique relies upon cyclostratigraphic data series collected from multiple stratigraphic sections of a given time interval, and the availability of independent time control (e.g., radioisotopic data). MIS stages and terminations, or other stratigraphic features, are adopted as control points that are time-correlative between each stratigraphic section. Independent time control is used to develop a preliminary sedimentation rate model at each section, from which the age of control points can be interpolated. The mean age of each control point across all sections, and its uncertainty, is then estimated (for additional method details, see Huybers and Wunsch, 2004). As originally applied, the objective was to retain variability in the signal that might be due to nonlinear climate change, where astronomical tuning tends to suppress such variability.

### Other Promising Techniques

Frequency-domain minimal tuning shows great promise for astronomical time scale construction, especially in Mesozoic and Paleozoic strata for which the time-domain astronomical targets are poorly constrained. This method, introduced by Park and Herbert (1987), applies time-frequency methods, such as evolutive harmonic analysis (Meyers et al., 2001) or wavelet analysis (Torrence and Compo, 1998), to evaluate the frequency drift of a dominant spatial bed- ding period. The temporal period associated with the “drifting” bedding cycle is constrained with independent time control (e.g., radioisotopic data; Meyers et al., 2001), or it is hypothesized to represent a particular Milankovitch term (e.g., short eccentricity; Park and Herbert, 1987).

Variable sedimentation rates are reconstructed by tracking the frequency drift of the spatial bedding period; integration of the sedimentation rate curve provides a time-depth map for tuning. Finally, the minimally tuned record can be evaluated by spectral analysis to determine if the other expected astronomical terms come into focus (Park and Herbert, 1987). The technique yields “floating” astronomical time scales (“Anchored” versus “Floating” Astrochronology subsection), which must then be anchored to radioisotopic data (Meyers et al., 2012).

One method among the efforts to build time scales without tuning cyclic strata to a prescribed astronomical target is “sedimentological tuning,” which has been underutilized despite demonstrated successes. The method assumes a constant accumulation rate for a minor sedimentary component, e.g., weight percent Al, and fluctuation in concentration is assumed to originate from variable accumulation of the remaining (much larger bulk of) sediment. Komiz et al. (1979) developed an “aluminum time scale” following this philosophy for the Pleistocene SPECMAP V28-238 δ18O record; correcting aluminum concentrations to a constant value by adjusting the time scale sharpened the power spectrum at the obliquity frequency. Herterich and Sarthein (1984) corrected fluctuations in the noncarbonate fraction to a constant rate in their carbonate-rich Brunhes section, which both increased obliquity and precession spectral power, and resolved 23 k.y. and 19 k.y. peaks in the precession band. A similar procedure was used by Herbert et al. (1986) to estimate carbon fluxes to the Cretaceous deep sea. Sedimentological tuning provides important independent evidence for astronomical control of stratigraphy without circular reasoning. The rise in XRF core scanning (Richter et al., 2006) should facilitate broader use of the technique in the future. Finally, another factor that is also under-appreciated in cyclostratigraphic research is the dramatic effect that turbidite identification and removal can have in clarifying the astronomical signal (Maurer et al., 2004).

### Astrochronologic-Radioisotopic Intercalibration

The goal of astrochronologic-radioisotopic intercalibration is to improve precision and accuracy of the geologic time scale. The grand challenge is to reduce geologic age uncertainty to the outcrop scale and ultimately to the bed- ding scale. When this is accomplished, credible study can begin on the correlation, timing, and duration of globally recorded geological events. The integration of high-precision radioisotope dating and astrochronology is an important step toward achieving these improvements.

The 40Ar/39Ar dating of feldspar and U-Pb dating of zircon have become the “gold standards” of high-precision radiogenic dating, and they make up the vast majority of the radioisotopic databases in recent geologic time scale compendia (e.g., Gradstein et al., 2012; Walker et al., 2013). Recently, researchers have reported full (analytical and systematic; Schoene et al., 2013) 2σ level 40Ar/39Ar and U-Pb age uncertainties that are on the order of 0.1% (Renne et al., 2013; Blackburn et al., 2013). That is, the attainable
Accuracy and Precision of Astrochronology

The quality of an astrochronology depends on correct identification of astronomical signals embedded in the stratigraphic record (e.g., precession vs. obliquity vs. noise) and the accuracy of the astronomical tuning target. In the case of radioisotopically anchored astrochronologies (“Anchored” versus “Floating” Astrochronology subsection), additional uncertainties arise from the radioisotopic ages themselves and, often times, their correlation into the astronomically tuned stratigraphic section. In addition to potential stratigraphic uncertainties (e.g., hiatuses), there are uncertainties in the climatic forcing leading to every cyclostratigraphic record, uncertainties in rotational effects on Earth’s precession constant through geologic time (Berger et al., 1992), and limitations in modeling prior to 50 Ma owing to chaotic behavior in past planetary motion (Laskar, 1990, 1994, 1997, 2008).

The manner in which these uncertainties contribute to a given astrochronology depends upon the age of the strata and the approach used to develop the astrochronology (see Astronomical Tuning subsection).

Insolation Season

Through the course of the year, the precession index forcing of insolation progressively changes its phase, as shown for October through April in Figure 4C. It is reasonable to assume that regional climate processes that might influence a stratigraphic record would tend to react to insolation during a specific season, or limited time of the year, for example, a rainy season with increased runoff to a depositional site. Unless there is other information indicating which month of the year the forcing had occurred, the chances for assuming the correct insolation season—i.e., a correct phasing for the precession cycles—are low. Thus, an insolation tuning target that includes precession forcing (e.g., the Pliocene sapropel sequence tuned to 65°N summer insolation plus a 3 k.y. lag; Lourens et al., 2004) will have a running uncertainty of about a half a precession cycle (10–12 k.y.).

Rotational Dynamics

As discussed in the Geophysical Parameters section, tidal dissipation through geologic time acts to decelerate Earth’s rotation (Fig. 5). Empirical evidence suggests that the present-day deceleration is valid at least to 25 Ma (Páll Ísleifsson and Shackleton, 2000). If deceleration is not taken into account, up to three precession cycles (or obliquity cycles) may be missed by 25 Ma (fig. 20.7 in Lourens et al., 2004). This uncertainty also affects the precession phasing of the seasonal insolation discussed earlier. Thus, for example, the interpretation by Kodama et al. (2010) for a late Eocene autumnal rainy season in Iberia relies on the validity of the La2004 tidal dissipation model.

The 405 k.y. Metronome

Earth’s orbit is influenced by the orbital perihelia of Venus and Jupiter, g2-g5, which impose the dominant 405 k.y. eccentricity cycle on Earth’s orbital eccentricity (Fig. 4A). The large mass of Jupiter guarantees robust modeling of this cycle over many hundreds of millions of years. Different models of g2-g5 produce 405 k.y. cycles with slightly discrepant phasing back through time, but the differences amount to only a few 405 k.y. cycles over the past 250 m.y. (Laskar et al., 2011). The 405 k.y. cycle dominates the orbital eccentricity variation as well as cyclostratigraphy and today serves as a basic “metronome” in astrochronology (Hinnov and Hilgen, 2012). An ongoing research objective is to identify all recorded 405 k.y. cycles for the astronomical time scale. If the 405 k.y. phasing problem can be solved, then Earth-Mars secular resonance can be reconstructed with more confidence and open the way for a better understanding of ancient solar system dynamics and the development of more accurate and precise tuning targets (see Ancient Solar System Dynamics section).

Model Limitations

Prior to 50 Ma, the time-domain astronomical models diverge due to initial condition uncertainties, integration error, and chaos (Laskar et al., 2004a, 2011; see also Ancient Solar System Dynamics section). Only the 405 k.y. orbital eccentricity cycle has relatively minor discrepancies amounting to a few cycles by 250 Ma. Sometime between 50 and 100 Ma, a “transition” occurred in the resonance state between the orbits of Earth and Mars. This would have affected the phasing of the 100 k.y. orbital eccentricity and the amplitude of the 405 k.y. orbital eccentricity cycle, i.e., the 2.4 m.y. modulation (Fig. 4A). Thus, when tuning to a time-domain astronomical model (Laskar et al., 2004a, 2011), the 405 k.y. cycle is the best option for times prior to 50 Ma, and it is also a desirable tuning target for cyclostratigraphy up to the present day due to its stability. Alternatively, statistical astronomical tuning to a frequency-domain target (Meyers and Sageman, 2007; Malinverno et al., 2010), followed by anchoring with radioisotopic data, provides the ability to develop reliable astrochronologies beyond 50 Ma. Because the time-domain and frequency-domain tuning approaches are independent, they can also be compared as a means for validation.

“Anchored” versus “Floating” Astrochronology

Today, most of the Cenozoic Era is composed of cyclostratigraphy that has been calibrated to time in yr B.P. with astronomical models at a 20 k.y. to ~100 k.y. resolution. This provides an “absolute” astronomically anchored astrochron-
Solar System Chaos

Chaotic behavior in the solar system was discovered in the course of numerical modeling over very long time periods (hundreds of millions to billions of years) (Laskar, 1989; Sussman and Wisdom, 1992). While the large outer planets maintain stable (quasi-periodic) orbits, models of the small inner planets display chaotic behavior with irregular modulations in orbital eccentricity and inclination, particularly Mars and Mercury (e.g., Laskar, 1996, 1997, 2008). The most recent of the chaotic episodes affecting Earth ended between 50–100 m.y. ago, but the precise timing is not known due to model error, which presently restricts accurate time-domain astronomical solutions for Earth to the interval 0–50 Ma (Laskar et al., 2011a). Thus, cyclostratigraphy can be used to guide solutions for times prior to 50 Ma.

Earth-Mars Secular Resonance

Resonances abound among the planets, and tracking resonance changes can help to quantify solar system chaotic behavior. An important secular resonance occurs between the orbital motions of Earth and Mars (g4-g3 and s4-s3), manifested as amplitude modulation terms in Earth’s orbital eccentricity (2.4 m.y.) and obliquity (1.2 m.y.) (Table 1: k+s3, k+s4, k+s+g3, k+g4, and k+g5). These modulations maintained these periodicities over much of the Cenozoic Era, reflecting 2:1 resonance, i.e., g4-g3 = 2(s4-s3) and a libration state between the orbits of Earth and Mars. This has been documented in cyclostratigraphy (Table 3; Shackleton et al., 1999; Bouilla et al., 2011, 2012; Westerhold et al., 2012 in Fig. 10b), although not both terms simultaneously.

Prior ca. 50 Ma, models indicate that the orbits of Earth and Mars transitioned through circulation states with 1:1 resonance, i.e., g4-g3 = s4-s3, as the result of chaotic diffusion (Laskar et al., 2004a, 2011a,b). There is also the possibility of 1:1 resonance in a separate libration state. The precise evolution of the resonance transitions may never be computationally determined with models, although new computer integration methods are now under development to push back the limitation to before 50 Ma (Blanes et al., 2013). For now, cyclostratigraphy must be consulted for the resonance history, with a key role for multimillion-year-long cyclic stratigraphic sequences (e.g., Figs. 10 and 11).

Table 3 summarizes cyclostratigraphy with interpreted long-term modulations thought to represent g4-g3 and s4-s3. Two sequences have provided both terms for evaluation of the Earth-Mars resonance state for the Mesozoic.

However, there are opportunities to reanalyze obliquity-forced cyclostratigraphy (e.g., the Jurassic Kimmeridge Clay, Cretaceous Scisti a Fucoidi) to evaluate s4-s3. Gathering this evidence is important for future solar system modeling, for example, to identify the most recent circulation-libration transition between the orbits of Earth and Mars. This transition is now predicted to have occurred at 50 Ma (Laskar et al., 2011a), but this requires cyclostratigraphic validation, for example, in the manner previously undertaken to evaluate the La1993 versus La2004 models over the interval 25–30 Ma (Pulíke et al., 2004).

Precession Resonance

The incorporation of a tidal dissipation factor in the La2004 astronomical model produces an obliquity variation with an increasing frequency (decreasing periodicity) and increasing tilt through geologic time (of ~0.5° per 250 m.y., see fig. 14 in Laskar et al., 2004a). A resonance occurs when the precession rate $k$ (estimated at 50.4576 arcsec/yr at present), which is decreasing through time, passes through a value equal to $s_5+g_5 = 50.336259$ arcsec/yr. The result is a drop in Earth’s axial tilt angle of ~0.4°, after which it resumes its slow increase. At present, the precession is very close to this resonance, and there has been speculation as to whether it could have already occurred due to the effect on $H$ by glacial loading (i.e., climate friction; see Climate Friction subsection) (Thomson, 1990; Laskar et al., 1993; Mitrovica and Forte, 1995; Xiang and Peltier, 1996; Mitrovica et al., 1997) or mantle convection (Forte and Mitrovica, 1997; Morrow et al., 2012).

MILANKOVITCH CYCLES ON MARS

Over the past 15 yr, high-resolution imaging and detailed analysis of Mars and its surface processes have been made possible by multiple orbital missions armed with an array of observing instrumentation and an eager community of scientists. The collected evidence depicts a richly dynamic history of paleoclimate change etched into the Martian landscape, thick sedimentary deposits in the low latitudes and highly structured ice caps at the poles (Malin and Edgett, 2000; Head et al., 2003, 2005; Carr and Head, 2010; Putzig et al., 2009). Today, there is an active climate marked by regional and global dust storms, erosion, and strong seasonality, but no persistent liquid water. The necessary ingredients for astronomical forcing of climate are present (Montmessin, 2006), and there is an emerging catalog of paleoclimate cycles preserved in the ice and sedimentary stratigraphy, discussed further next.
Mars Climate System

Temperature and Seasonality

Mars surface temperatures are much lower than Earth’s, with a mean temperature of ~–63 °C (Williams, 2013), an atmospheric lapse rate half that of Earth (Leovy, 2001), and, depending on latitude, daily and seasonal surface temperature swings of up to 100 °C (Zurek et al., 1992; Leovy, 2001; Liu et al., 2003a). The contrast in heating between the northern and southern hemispheres, particularly during southern summer (northern winter), leads to development of large wind systems and global dust storms lasting weeks to months.

Seasonal CO₂ ice accumulates and sublimates at both poles. The permanent north polar ice cap is dominantly H₂O, while the south polar ice cap has significant CO₂ deposits (Byrne, 2009; Phillips et al., 2011). Since the Martian aphelion/ perihelion distance ratio is large, the north pole has a significantly colder summer (~30 °C colder) compared with the south pole. This could explain why the northern ice cap is larger than the southern ice cap (Byrne, 2009). This is the case despite a shorter southern summer (150 sols) and longer northern summer (180 sols).

The Mars Orbiter Laser Altimeter (MOLA) measurements (Byrne, 2009) indicate that the north polar ice cap (“Planum Boreum”) is raised above the surrounding terrain by ~2 km at its center, and thins away from the pole over 400–500 km. It has outwardly spiraling lobes and a deep canyon (“Chasma Boreale”) on one side. The south polar ice cap (“Planum Australe”) is offset from the rotational pole with a diffuse morphology and a 3-km-thick ice cap, compared with the 2-km-thick north polar ice cap.

The Mars Orbital Camera (MOC) and High Resolution Imaging Science Experiment (HiRISE) have provided images of the ice caps with detailed views of the chasms, revealing intricate layering patterns likely due to variable amounts of dust incorporated into the ice (Milkovich and Head, 2005; Milkovich et al., 2008; Hvidberg et al., 2012). Shallow Radar (SHARAD) soundings reveal that the caps also have a pronounced internal stratigraphy (Putzig et al., 2009; Phillips et al., 2011).

Analysis of Mars surface morphology indicates that ice redistribution into the low latitudes took place within the past 2 m.y. (Head et al., 2003, 2005), and that Mars is presently in an interglacial period with permanent ice restricted to the polar latitudes. During periods of low-amplitude obliquity variability (nodes in the obliquity curve), the poles receive less maximum solar radiation, likely resulting in polar ice cap expansion. When obliquity variations amplify into wider extrema (see Cyclostratigraphy on Mars subsection), polar ice could undergo dramatic growth/melt cycles extending into the lower latitudes (Mischna et al., 2003).

Dust

The Martian atmosphere is very thin (6 mbar), rich in CO₂, and has a large Hadley circulation that activates dust storms near the polar ice boundaries preferentially during northern winter (Leovy, 2001; Liu et al., 2003a). The contrast in heating between the northern and southern hemispheres, particularly during southern summer (northern winter), leads to development of large wind systems and global dust storms lasting weeks to months.

TABLE 3. STRATIGRAPHIC EVIDENCE FOR LONG-TERM MODULATIONS RELATED TO SECULAR RESONANCE OF EARTH-MARS

<table>
<thead>
<tr>
<th>Stratigraphic record</th>
<th>g4-g3 (period in m.y.)</th>
<th>g3-g2 (period in m.y.)</th>
<th>Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>NEOGENE</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pleistocene–Miocene (0–9 Ma)</td>
<td></td>
<td>1.2</td>
<td></td>
</tr>
<tr>
<td>Miller et al. (2005); Boullia et al. (2011)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Miocene–Oligocene (20–34 Ma)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Benthic marine δ¹⁸O</td>
<td></td>
<td>1.2</td>
<td></td>
</tr>
<tr>
<td>Ocean Drilling Program (ODP) Site 1218</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pálk et al. (2006); Boullia et al. (2011)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>PALEOGENE</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Eocene–Palaeocene (47–53 Ma)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ODP Sites 1258, 1262</td>
<td>2.4</td>
<td>2.0</td>
<td>–</td>
</tr>
<tr>
<td>Westerhold et al. (2012)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CRETACEOUS</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Maastrichtian–Campanian (60–84 Ma)</td>
<td></td>
<td>1.7</td>
<td>–</td>
</tr>
<tr>
<td>Deep See Drilling Project (DSDP) Site 516F Herbert (1999)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CRETACEOUS</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Turonian–Campanian (82–92 Ma)</td>
<td></td>
<td>1.5</td>
<td>–</td>
</tr>
<tr>
<td>Songliao Basin, China</td>
<td>2.9–2.6</td>
<td>3.1</td>
<td>1.5:1–1.3:1</td>
</tr>
</tbody>
</table>
Astronomical Parameters of Mars

Milankovitch cycles on Mars were being considered before they were widely accepted for Earth (Murray et al., 1973; Ward, 1973, 1974; Toon et al., 1980). Since solar system models provide orbital element solutions for all the planets, astronomical forcing parameters for any planet can be extracted and investigated. Thus, the La2004 model of Laskar et al. (2004a) has been evaluated for the Martian orbital elements (Fig. 13), but using precession equations specific to Mars (Laskar et al., 2004b). As with Earth, Mars insolation entails contributions from the three astronomical parameters and can be calculated with Equation 4 adapted for Mars (see Astronomically Forced Insolation and the Climate System Response section).

The periodicities of the Martian astronomical parameters are familiar, although they appear in different guises: Orbital eccentricity has a major 2.346 m.y. cycle related to g4-g3 (Fig. 13A); Earth’s orbital eccentricity has a small direct term at this period, but notably it appears as a strong modulator of the 405 k.y., 128 k.y., and 98 k.y. cycles (Fig. 4A). Mars does not have a 405 k.y. eccentricity cycle, whereas it is the dominant cycle in Earth’s orbital eccentricity. However, it appears as an amplitude modulator of Mars’ ~100 k.y. eccentricity cycles, i.e., 1/(94.6 k.y.) – 1/(125 k.y.) = 1/(400 k.y.); this is visible in the bundling of the cycles (Fig. 13A). The precession rate for Mars, k_Mars, is 7.576 arcsec/yr, which is much slower than Earth’s 50.4576 arcsec/yr, and this leads to obliquity and precession index cycles with ~100 k.y. periodicities (Figs. 13C–13F). Lack of precision in k_Mars limits accurate modeling of the obliquity and precession index to the most recent 10 m.y. of Martian history. As with Earth, the obliquity variation for Mars has strong amplitude modulations related to the s3-s5 and g2-g3 terms (see Ancient Solar System Dynamics section).

One observation of special note is the strong decline at 5 Ma in the obliquity variation from an average obliquity of 0.65 rads to 0.45 rads (37.2° to 25.8°) (Fig. 13C). This shift was the result of Mars passing through a spin-orbit secular resonance originating from the orbital inclination (Ward and Rudy, 1991). This is analogous to the iminent Earth precession resonance and predicted future decline in Earth’s obliquity angle (see Precession Resonance subsection; Touma and Wisdom, 1993).

Tidal dissipation on Mars originates virtually exclusively from the Sun and is negligible; it is supposed that Mars has maintained its current rotation rate through most of its history (Laskar et al., 2004b). The Martian moons Phobos and Deimos are too small to contribute significantly to dissipation. Mantle convection, core-mantle friction, and climate friction are also negligible factors. Ward et al. (1979) and Armstrong et al. (2004) investigated the change in Mars’ shape from the emplacement of Tharsis. Prior to Tharsis, which was emplaced early in Martian history (Phillips et al., 2001), obliquity of Mars would have been lower and less stable.

Cyclostratigraphy on Mars

Over the past decade, high-resolution imaging of the Martian surface has invigorated planetary science. An ever-increasing subset of these images depicts strong stratification of sedimentary and ice cover, compelling scientists to explore whether Milankovitch-forced climate could have generated these accumulated patterns. First, layered polar ice was investigated, followed later by quasi-periodic sedimentary sequences.

Ice

Layering in the polar ice caps was discovered 40 yr ago with the Mariner spacecraft television camera (Murray et al., 1972; Soderblom et al., 1973; Cutts, 1973). The discovery inspired the Milankovitch theory of climate change for Mars (see Astronomical Parameters of Mars subsection), but actual measurements of the layering was not possible until the Mars Orbiter Camera (MOC) returned meter-scale-resolution images of the Martian surface and its stratigraphic details (Malin and Edgett, 2001).

Soon thereafter, Laskar et al. (2002) visually correlated 250 m of vertical ice dust layering patterns captured in MOC image M00–02100 from a trough wall in the north polar cap (86°N, 279°W) to astronomically forced insolation calculations. In the absence of a time scale for the image, they speculated that the sequence represented ~500,000 yr of deposition. Subsequently, Milisavljevic and Head (2005) and Milkovich et al. (2008) examined MOC images from other locations, discovering that stratigraphic patterns from the uppermost 300 m are correlated around the cap and have a dominant ~30 m wavelength. This built a case for regional forcing of ice dust accumulation and support for Laskar et al.’s (2002) Milankovitch
interpretation. The statistics of the stratigraphic patterns were addressed by Perron and Huybers (2009), who applied spectral and wavelet analysis on the 350-m-long MOC image M0001754, revealing an ~30 m cycle in the upper 150 m and an ~1.6 m cycle sporadically throughout the image. Fishbaugh et al. (2010) constructed a high-resolution stratigraphic column for the upper 400 m of the north polar ice cap, tied to a digital elevation model, in which the 30 m cycle figures prominently. Most recently, an ice and dust accumulation model forced by Milankovitch cycles was proposed by Hvidberg et al. (2012) in an attempt to explain the layering and to develop a model chronology for the ice stratigraphy.

The overriding chronology issue that has limited all of these studies is reminiscent of the Earth ice chronology problem. It might be feasible, for example, to develop ice chronologies based on ice-flow physics analogous to those developed for Earth’s polar ice sheets (Dansgaard and Johnsen, 1969; Johnsen and Dansgaard, 1992; Parrenin et al., 2004, 2007).

Sedimentary Rocks

The majority of sedimentary rocks discovered thus far on Mars occur in the low latitudes between 30°S and 20°N (Grotzinger et al., 2011; Kite et al., 2011). The High Resolution Imaging Science Experiment (HiRISE) (McEwen et al., 2007) provides spectacular images of sedimentary rocks, and among them are startling images of rhythmically bedded sequences, in particular, across the Arabia Terra region.

Among the opportunities to study these rhythm sequences was one exposed within Becquerel Crater (22°N, 352°E). Analysis of a grayscale scan taken vertically through HiRISE image PSP_001546_2015 shows that bedding consists of basic 3–4 m cycles grouped into bundles of 10, i.e., 30–40 m cycles (Figs. 13G–13J; Lewis et al., 2008). This pattern is most similar to that of Mars’ obliquity variation (compare to Figs. 13C–13D); if each basic cycle is an ~116 k.y. obliquity cycle, then the 300-m-thick sequence represents nearly 12 m.y. of deposition. As with the ice stratigraphy, as yet no independent chronology exists to verify this calibration or the age of the deposit. The composition of the sediments and their depositional environment are also not yet known, although an eolian origin seems likely.

Numerous other rhythmic sequences are under investigation (Lewis, 2009). It may be fruitful to apply the recently developed average spectral misfit technique (see Astronomical Tuning subsection) to test hypotheses for Milankovitch forcing on Mars. However, the first order of business for reconstruction of the Mars’ time scale will have to proceed with evaluation of stratigraphically controlled crater counts and the law of superposition (e.g., Page et al., 2009; Neukum et al., 2010), much as it has taken place, albeit with fossils in place of craters, here on Earth.

SUMMARY AND OUTLOOK

Cyclostratigraphy has developed from a tentative hypothesis in the mid-twentieth century into a robust theory and independent discipline today, with specializations in sedimentology, geochemistry, integrated stratigraphy, paleontology, geochronology, geophysics, tectonics, astronomy, paleoclimatology, and paleoceanography. It has fueled development of new statistical techniques in time-series analysis and modeling. The science has demonstrated the global and interplanetary (to Mars) reach of Milankovitch cycles, which when recognized in cyclostratigraphy can be used for global correlation of the geologic record. Since Mars and Earth orbital frequencies are shared, there is a real “interplanetary correlation” potential for their cyclostratigraphies. In the not too distant future, we should expect that comparative planetology of Mars and Earth will include a strong component in cyclostratigraphy.

The deterministic attributes of Earth’s astronomical forcing paleoclimate record have been shown to comprise a high-resolution time scale, which enhances and supports other geochronometers (e.g., radioisotope dates). Thus, cyclostratigraphy has acquired aspects of applied science, and today is a required tool for future development of the geological time scale (Gradstein et al., 2012).

Cyclostratigraphic science is young yet, with surprises arising from unexpected places. Effects of obliquity and orbital eccentricity on the geodynamo have been sought (e.g., Liu et al., 2003b; Roberts et al., 2003; Fuller, 2006), although the geological record of geodynamo behavior is difficult to assess, and no clear connection has been made. The effect of orbital eccentricity on the ocean tides has been investigated (DeBoer and Trabuco Alexandre, 2011) in an effort to explain strong eccentricity cycles recorded in stratigraphy that presently are ascribed to glacio-eustatic change, even for ice-free ages (e.g., the Triassic). Over the past 1.2 m.y., Pacific volcanic eruption activity had a 41 k.y. modulation thought to be related to crustal stress changes from loading-unloading of glacial ice in tune with obliquity (Kutterolf et al., 2012).

Finally, Milankovitch forcing has implications in determining the habitability of exoplanets (Spiegel et al., 2010). Earth’s orbital configuration relative to its star, including its spin rate, obliquity, and eccentricity (Spiegel et al., 2009; Dressing et al., 2010), provides a baseline configuration by which to assess planetary habitability in other planetary systems. Increasing our knowledge about the paleoclimate of Mars will help to place additional constraints on orbital-rotational conditions necessary for planetary habitability, at least for life forms that are compatible with Earth.

Figure 13 (on following page). Astronomical parameters of Mars and their 2π multitaper power spectra for the past 10 m.y. according to the La2004 model (Laskar et al., 2004b). Labels indicate periodicity in k.y.; Δt = 1/T, where T = 10 million years for the Laskar time series and T = 300 m for the Mars stratigraphic series. (A) Orbital eccentricity (red curve) with 400 k.y. modulation (black curve). (B) Power spectrum of the 10-m.y.-long orbital eccentricity; the 400 k.y. term does not appear in the spectrum because it is a modulator of the 125 k.y. and 94.6 k.y. terms. (C) Obliquity variation in radians (red curve) with 1260 k.y. and 2346 k.y. modulations (black curves). (D) Spectrum of the 10-m.y.-long obliquity variation with a 10% weighted average removed (to subtract the step-up between 3 and 5 Ma). Closely spaced terms in the 116 k.y. band (not labeled) are responsible for the two modulations depicted in C. (The spectrum detects power at the modulation frequencies owing to an imperfect weighted average that was used for removing the step-up.) (E) Precession index (red curve) with a major 2346 k.y. modulation (black curve). Not highlighted are shorter modulations at 400 k.y. and ~100 k.y. periods, analogous to Earth’s precession index. (F) Spectrum of the 10-m.y.-long precession index. (G) Detrended grayscale scan of quasi-periodic stratigraphy from image PSP 001546 2015 at Becquerel Crater (22°N, 352°E) on Mars. (H) Spectrum showing basic sedimentary cycles with 3–4 m thickness bundled into groups of 10 with 30–40 m thickness. (I) High Resolution Imaging Science Experiment (HiRISE) image PSP 001546 2015 from Becquerel Crater (22°N, 352°E) on Mars. (J) Image PSP 001546 2015 shown draped over digital stereo topography to correct for tilt. Images in I and J are from high-resolution images provided in Lewis (2009).
Cyclostratigraphy and revolutionizing applications

Figures A, B, C, D, E, F, G, H, I, J show various plots and diagrams illustrating the cyclostratigraphy and its applications. The plots include time series data and frequency spectra, with axes labeled in ka BP (thousand years before present) and cycles/k.y.

The diagrams indicate the power (brightness^2/Δf) and other parameters over time. The text accompanying these figures provides context for the cyclostratigraphic analysis and its implications in geology.

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APPENDIX


HIRISE: http://hirise.lpl.arizona.edu.

REFERENCES CITED


