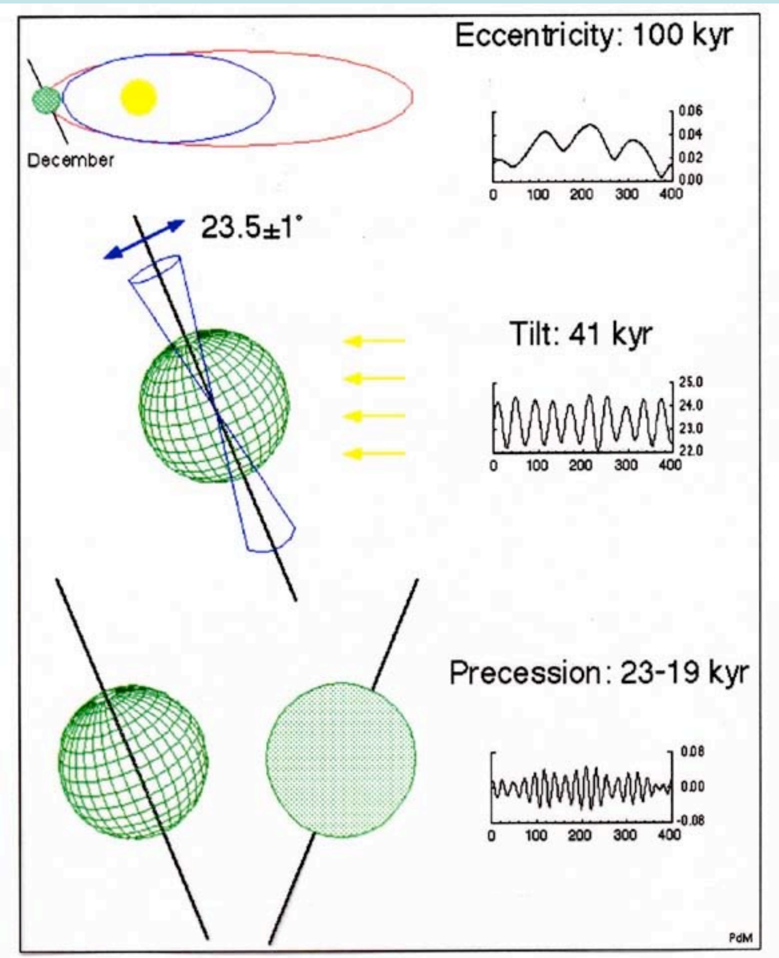
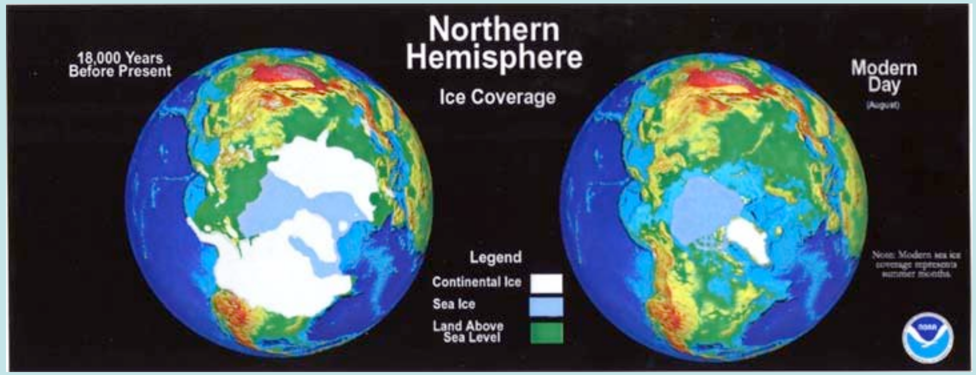
12.842 / 12.301 Past and Present Climate
Fall 2008

Pleistocene Ice Age Cycles 0-2.65 ma

12.842 Lecture 7 Fall 2008

Pleistocene Glaciations





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Citation: See image in Petit, et al. (1999) in Kump(2002) *Nature*, 419:188-190.

• Urey (1947) calculated that the oxygen isotope fractionation between calcium carbonate and water should be temperature-dependent.

$$\delta^{18}O = 1000\left[\frac{R_{sample}}{R_{standard}} - 1\right]$$

• Epstein (1953) grew molluscs in the laboratory and empirically determined the O18-T relationship:

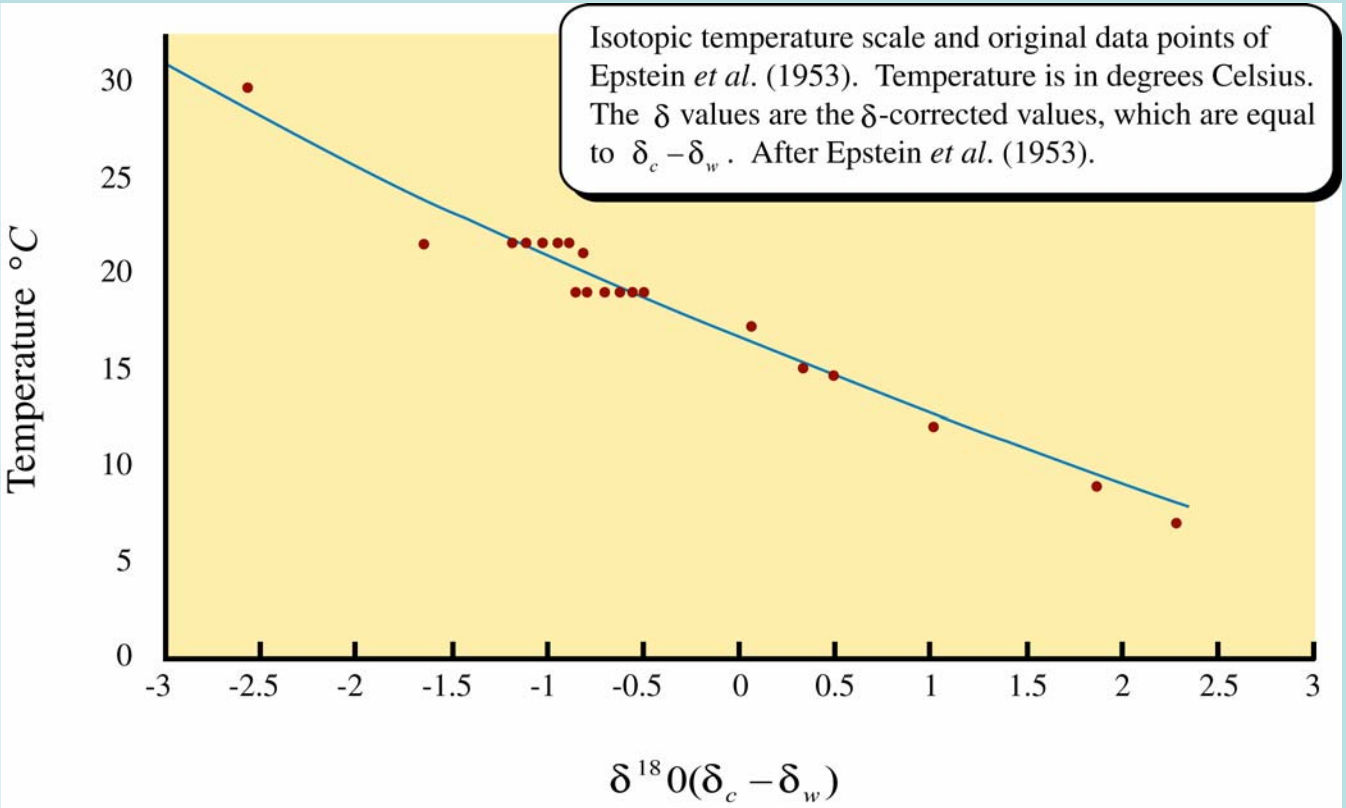


Figure by MIT OpenCourseWare.

• Emiliani (1955 and other papers) analyzed foraminifera from piston cores from the deep sea, and made temperature estimates:

• He found multiple cycles of cold and warm periods during the past ~500,000 years.

2. This work created quite a stir, and quickly was criticized on several grounds:

a. It violated the prevailing 4-ice-age theory from continental geology.

b. Meteorologists though that the tropical temperature change seemed excessive.

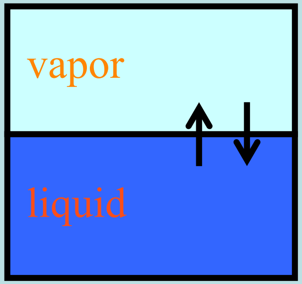
c. Micropaleotologists thought that their micropaleontological work (G. menardii stratigraphy) contradicted with O-18 record.

d. Biologists (e.g. Bé) argued that foraminiferal ecological shifts may have altered the depth habitat of organisms (and hence temperatures).

e. The time scale (based on $^{230}Th/^{231}Pa$) was criticized.

f. Various statistical errors were pointed out.

Rayleigh distillation of oxygen isotopes



Vapor pressure = f(T)
(Clausius-Clapeyron equation, exponential with increasing T)

At 25°C, the vapor pressure of $H_2{}^{16}O$ is 0.9% higher than $H_2{}^{18}O$

Imagine a 50-50 mixture of liquid $H_2{}^{16}O$ and $H_2{}^{18}O$, equilibrated with the vapor phase at 25°C. Separate the vapor from the liquid:

$\delta^{18}O$ = -9‰ T=25°C

1009 $H_2{}^{16}O$ 1000 $H_2{}^{18}O$

Cool the vapor to 20°C; allow liquid to condense from vapor:

$\delta^{18}O$ = -11‰ T=20°C

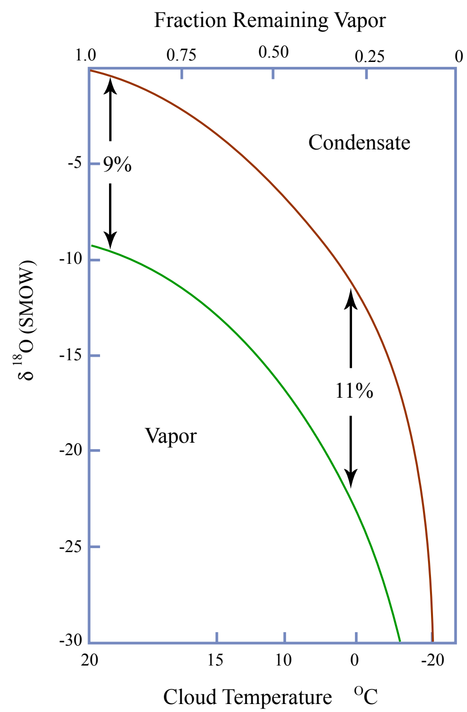
745 $H_2{}^{16}O$ 737 $H_2{}^{16}O$

264 $H_2{}^{16}O$ 263 $H_2{}^{18}O$

Rayleigh equation: $$\frac{R}{R_0} = f^{\alpha-1}$$

R_0 = initial isotope ratio
R = isotope ratio after cooling
f = fraction of water condensed
α = isotope fractionation factor

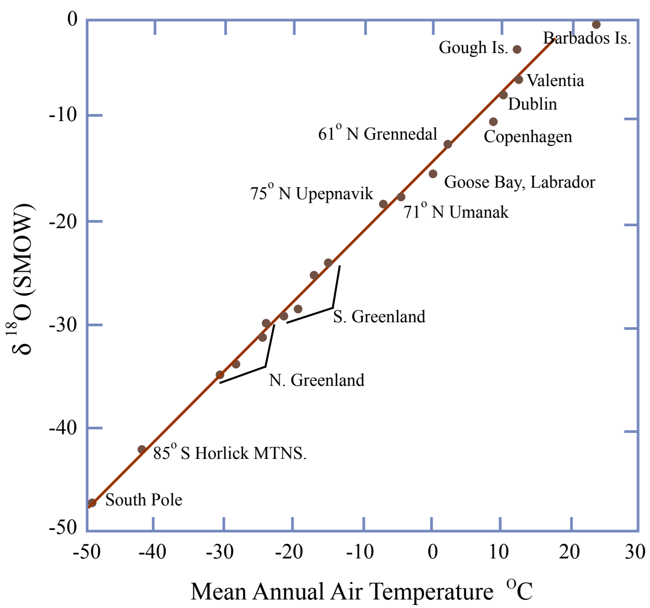
Cumulative Rayleigh Isotope Distillation as a function of temperature



$\delta^{18}O$ in cloud vapor and condensate plotted as a function of the remaining vapor in the cloud for a Rayleigh process. The temperature of the cloud in degrees Celsius is shown on the lower axis. $\delta^{18}O$ values are relative to SMOW. The increase in fractionation with decreasing temperature is taken into account. After Dansgaard (1964).

Figure by MIT OpenCourseWare.

Observed $\delta^{18}O$ - surface temperature relationship

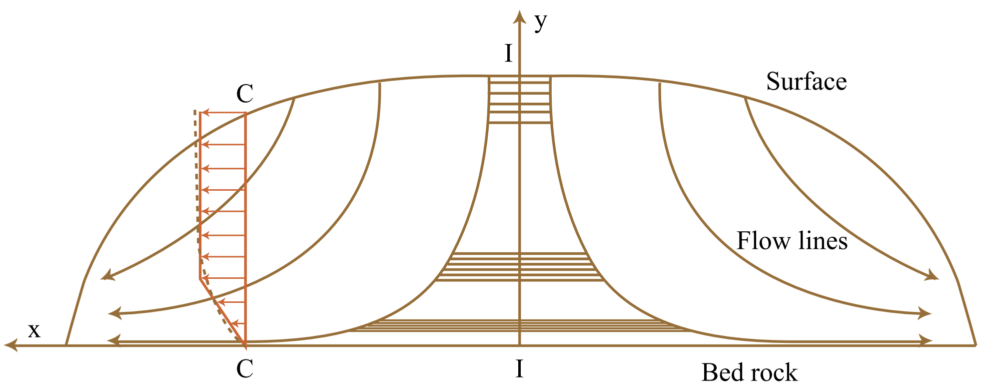


Mean annual $\delta^{18}O$ of precipitation as a function of the mean annual air temperature at the earth's surface. Note that $\delta^{18}O$ values are progressively lighter as the mean annual temperature becomes lower. After Dansgaard (1964).

Figure by MIT OpenCourseWare.

Note: this line is <u>not</u> the relationship predicted by the Rayleigh distillation curve. It includes many other effects: evaporation-precipitation cycles, cloud-T / surface-T relationships; multiple sources of water vapor at different temperatures, etc.

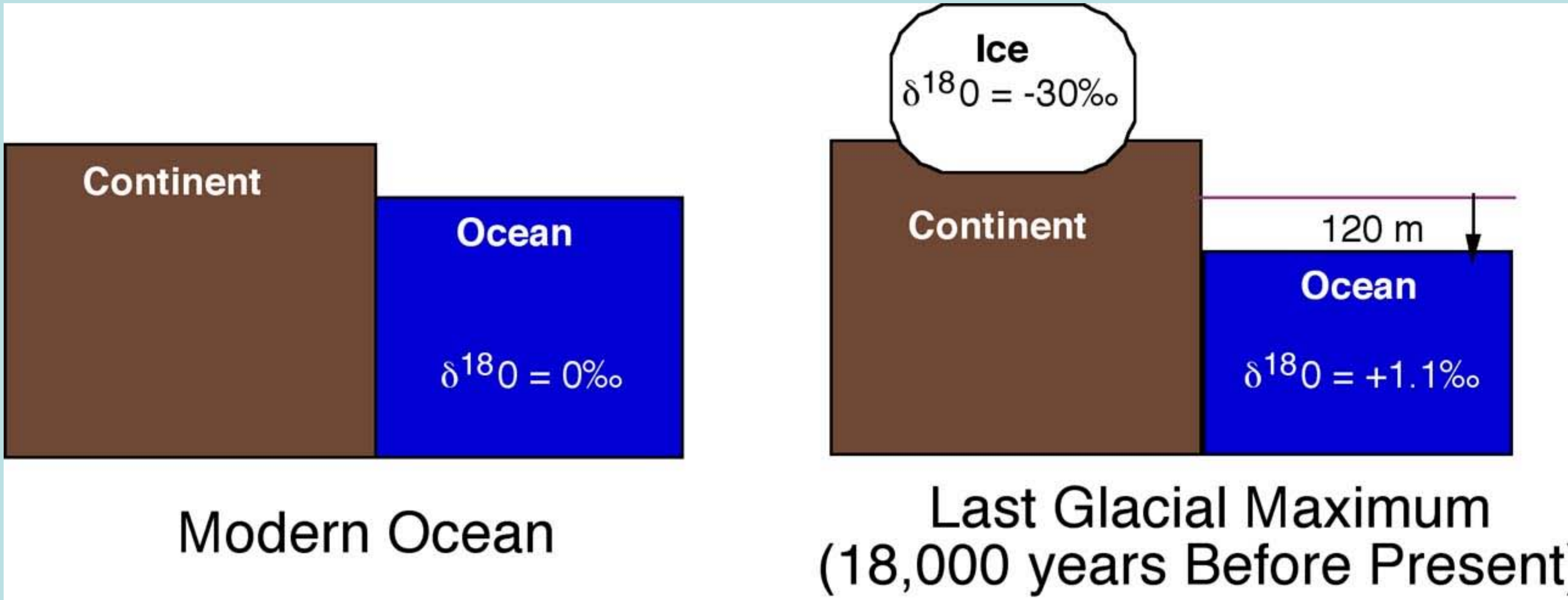
Because they flow, glaciers are filled from their summits:



Vertical cross section of an ice sheet resting on a horizontal subsurface. Ice particles deposited on the snow surface will follow lines that travel closer to the base the farther inland the site deposition. An ice mass formed around the divide (I-I) will be plastically deformed (thinned) with depth as suggested by the lined areas. The dashed curve along the vertical ice core (C-C) shows the calculated horizontal velocity profile V_x (Weertman 1968b). The horizontal arrows along C-C show the adopted approximation to V_x (Dansgaard et al. 1969).

Figure by MIT OpenCourseWare.

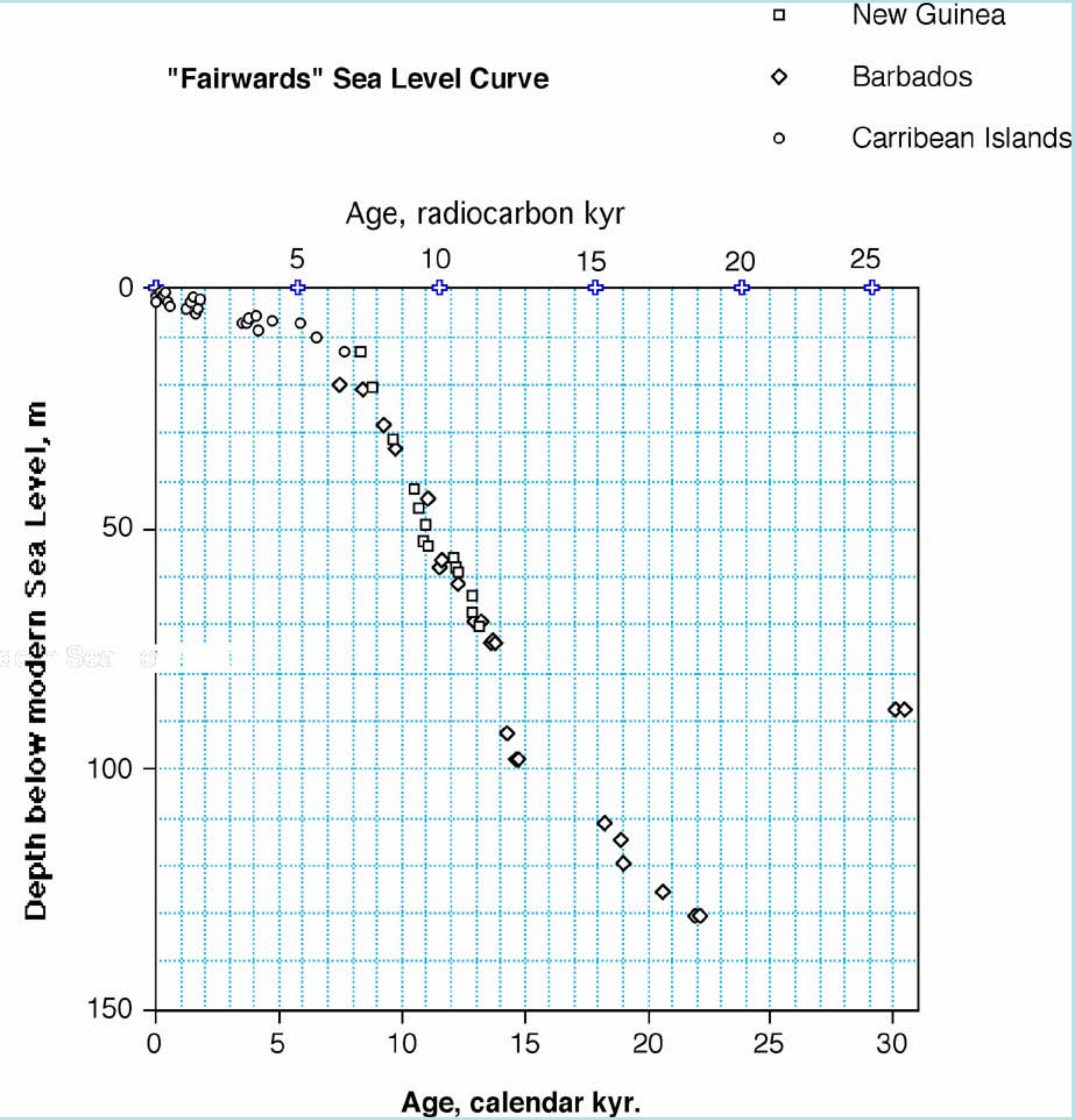
Effect of glaciation on the oxygen isotope composition of the ocean

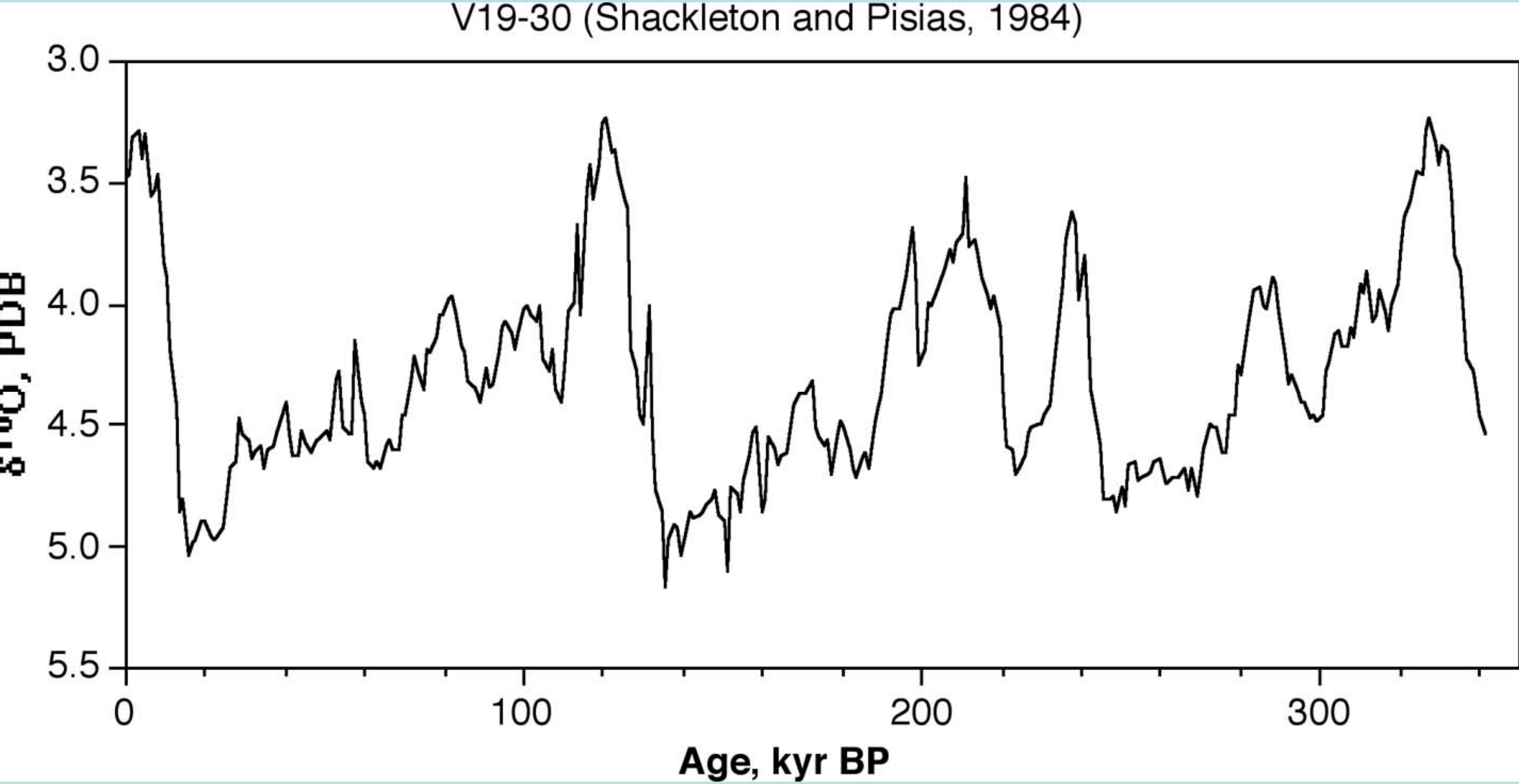


Isotope Mass Balance Equation:

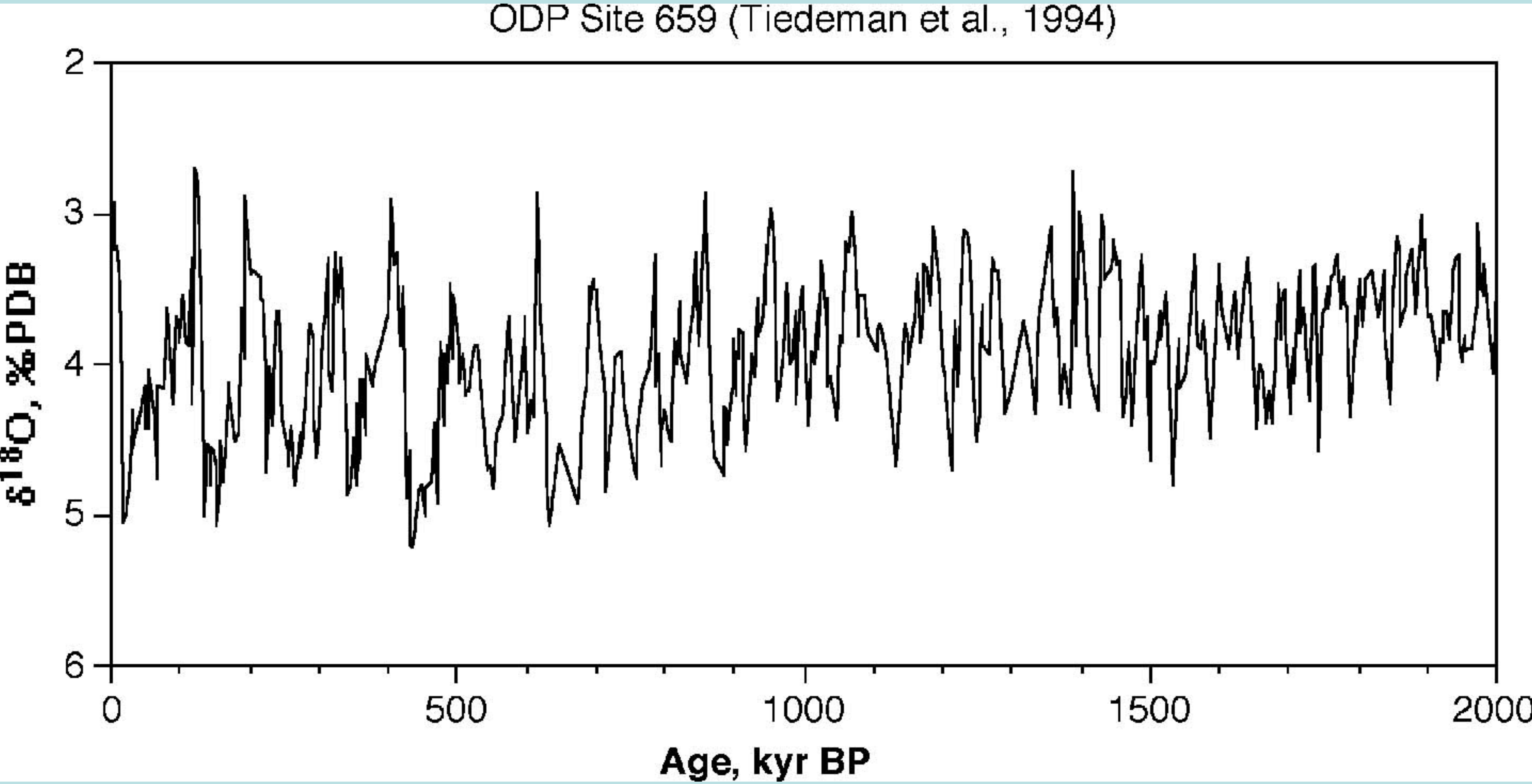
$$M_o\delta_o + M_i\delta_i = M_t\delta_t$$

Sea-level estimates from drilling submerged coral terraces





V19-30 (Shackleton and Pisias, 1984)
3.0
3.5
4.0
4.5
5.0
5.5
δ18O, PDB
0
100
200
300
Age, kyr BP



ODP Site 659 (Tiedeman et al., 1994)
2
3
4
5
6
δ18O, ‰PDB
0
500
1000
1500
2000
Age, kyr BP

Earth’s Orbital Geometry:

The Milankovitch Hypothesis & the Pacing of Pleistocene Ice Ages

Milankovitch Hypothesis: Historical Perspective

<u>What</u>: Astronomical theory of Pleistocene ice ages.

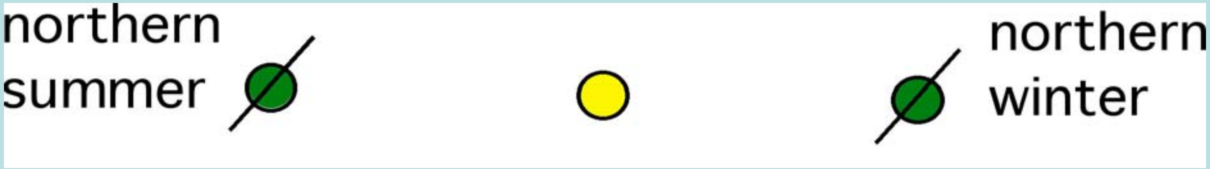
<u>How</u>: Varying orbital geometry influences climate by changing seasonal & latitudinal distribution of solar radiation incident at top of atmosphere (insolation).

<u>Milestones: Hypothesis</u>

- <u>Croll (1864, 1875)</u>: Proposed that variations in seasonal influx of energy--the cumulative affect of eccentricity, obliquity & precession--could trigger large climate response.

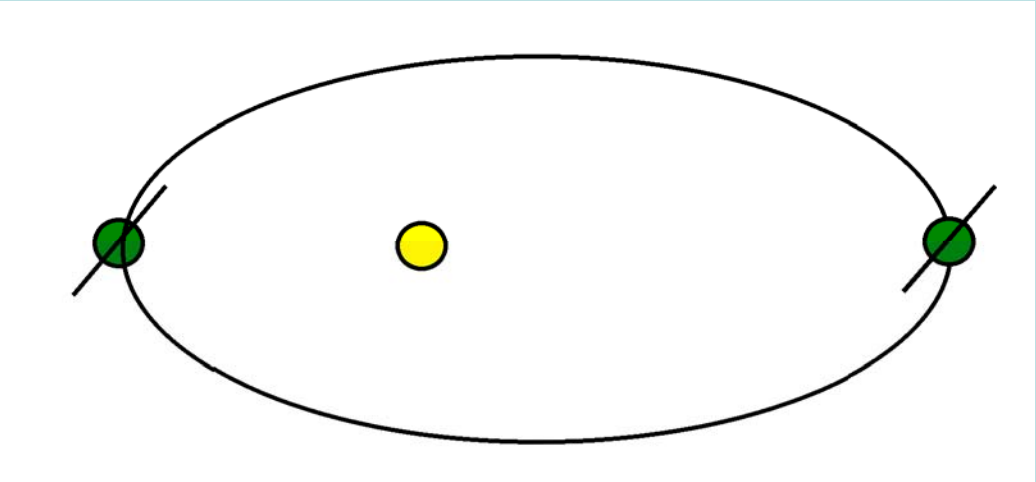
- <u>Milankovitch (1920, 1941)</u>: Combined laws of radiation with planetary mechanics to derive insolation curves as function of time (600 kyr) and latitude. Concluded summer insolation at high N. lat. (65°N) critical to growth/decay of ice sheets. "The Milankovitch Hypothesis".

The Seasons



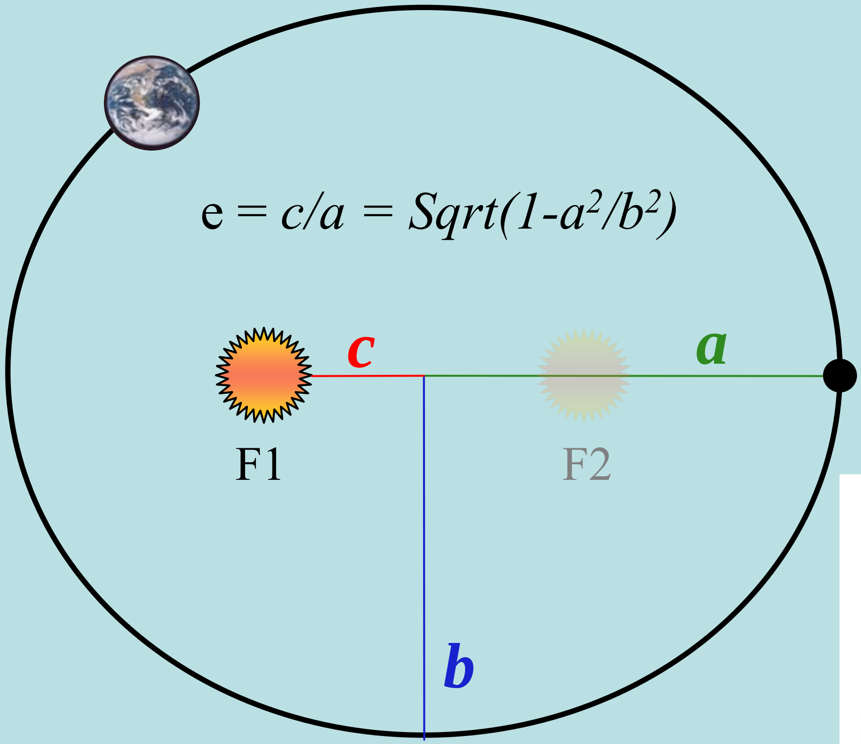
(edge view)

The seasons in an elliptical orbit

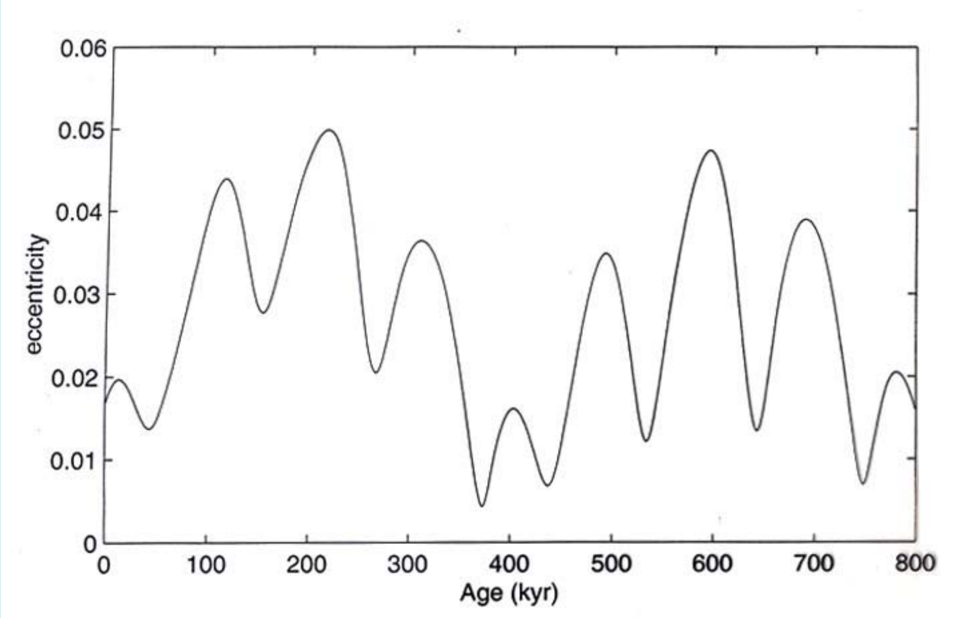


(oblique view, exaggerated eccentricity)

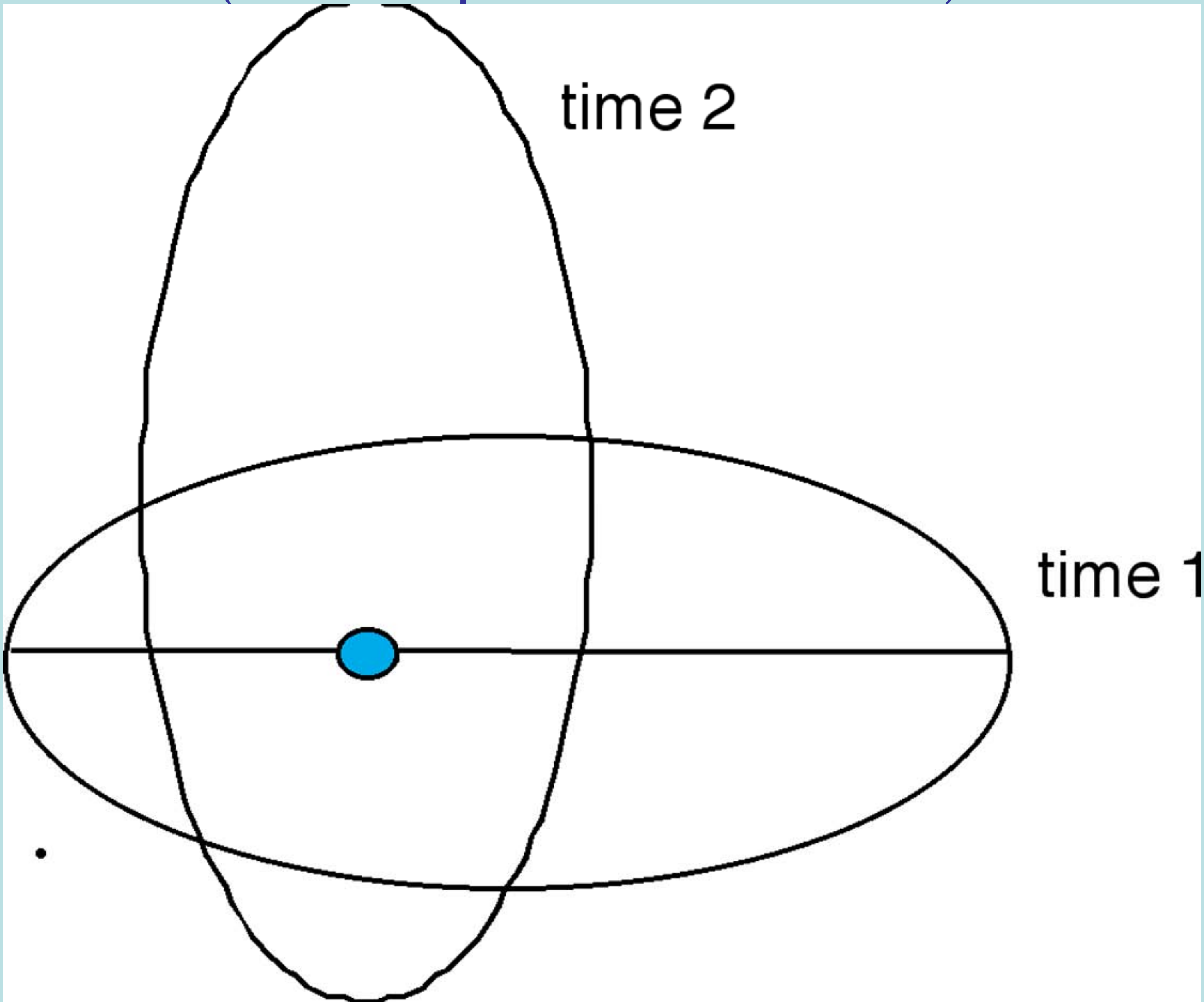
Eccentricity of Present Earth Orbit Around Sun (to Scale)



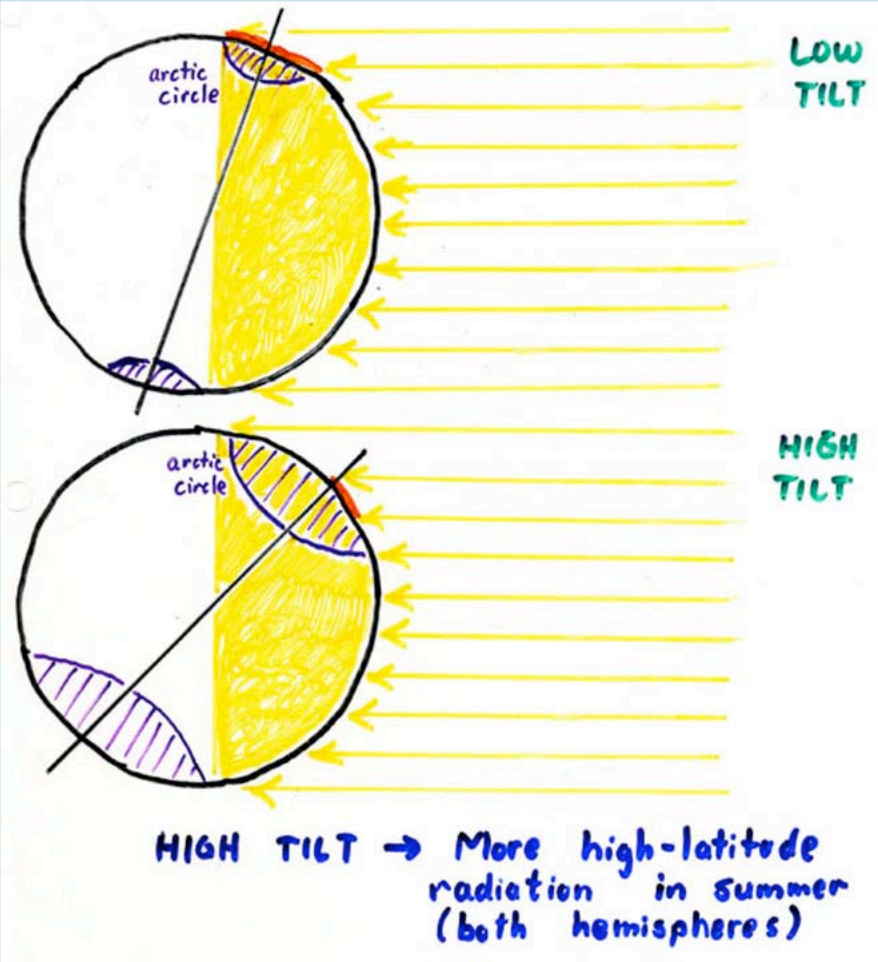
Present eccentricity = 0.017
Range: 0 - 0.06
100 & 400 kyr periods

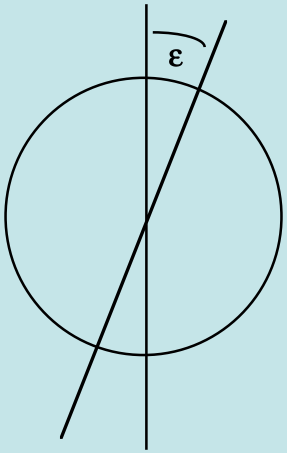


Precession of elliptical orbit (with respect to fixed stars)

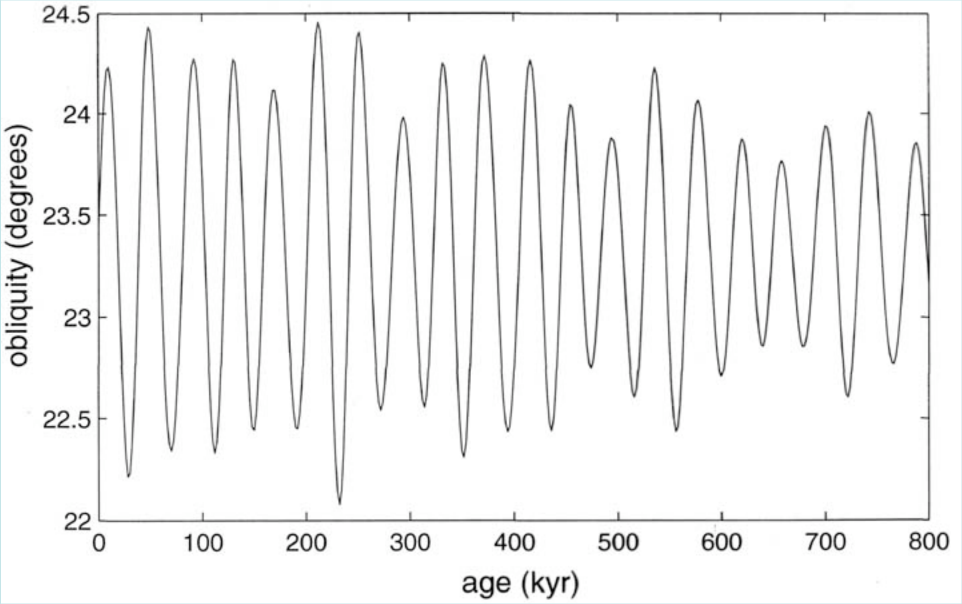


Obliquity (tilt)



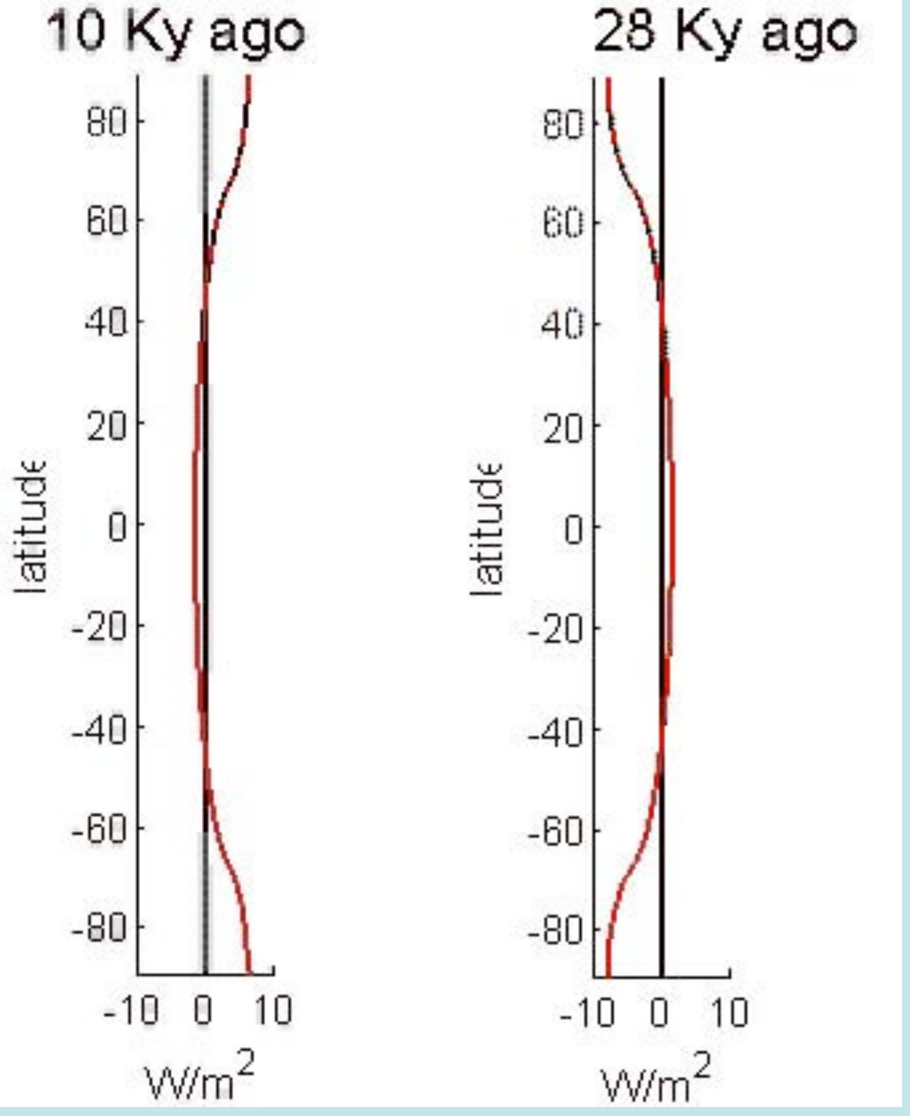


Obliquity varies between ~21.8° and 24.4°; at present the obliquity is 23.44°. Affects the latitude of the tropics and the arctic circle. Period is ~41,000 years, and is relatively regular. Think of this as part of a solar system angular momentum oscillator (angular momentum conserved in solar system, but with transfers between objects)

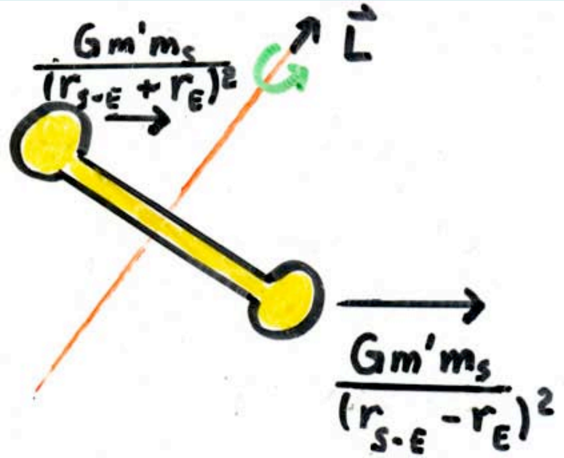


Higher obliquity leads to higher summer insolation at high latitudes (and slightly less at low latitudes).

Obliquity change re-apportions radiation between polar regions and tropics



Precession



Precession frequency depends on angular momentum and torque

P = 25,700 years

Eccentricity amplitude-modulates precession parameter

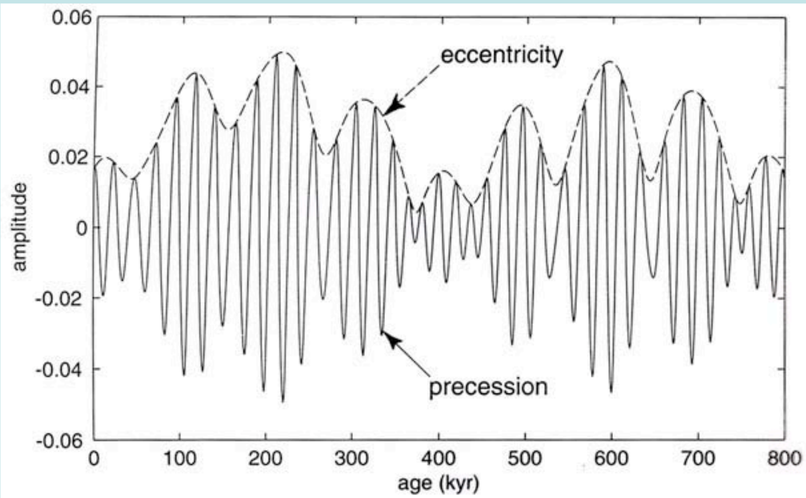
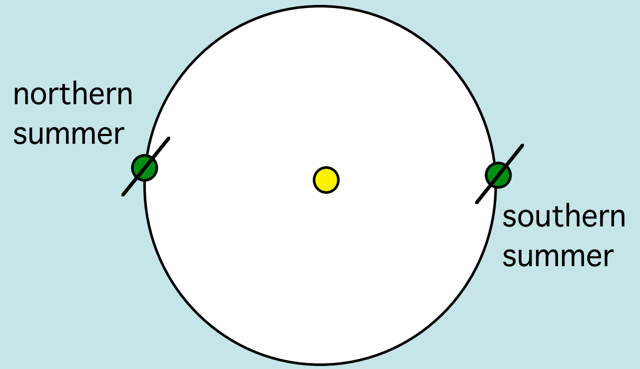
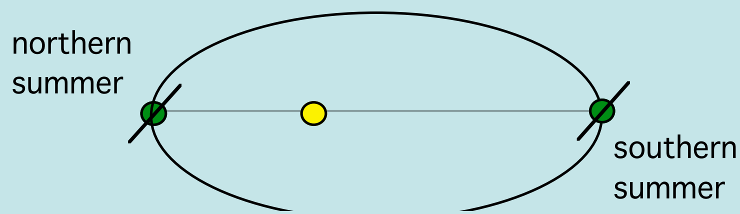


Fig. 2.10. Precession parameter p and eccentricity.

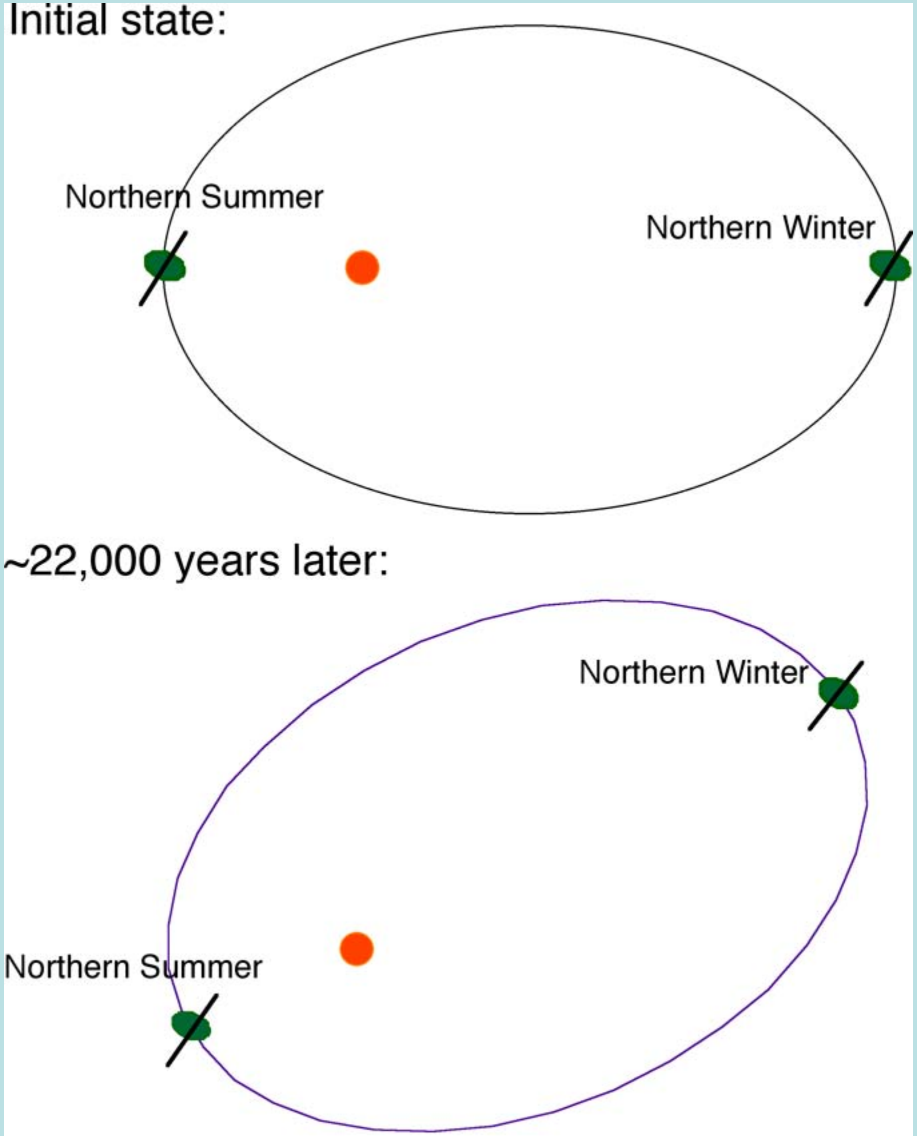
$p = e \sin \omega$

↑ ∠ between Spring Equinox + perihelion



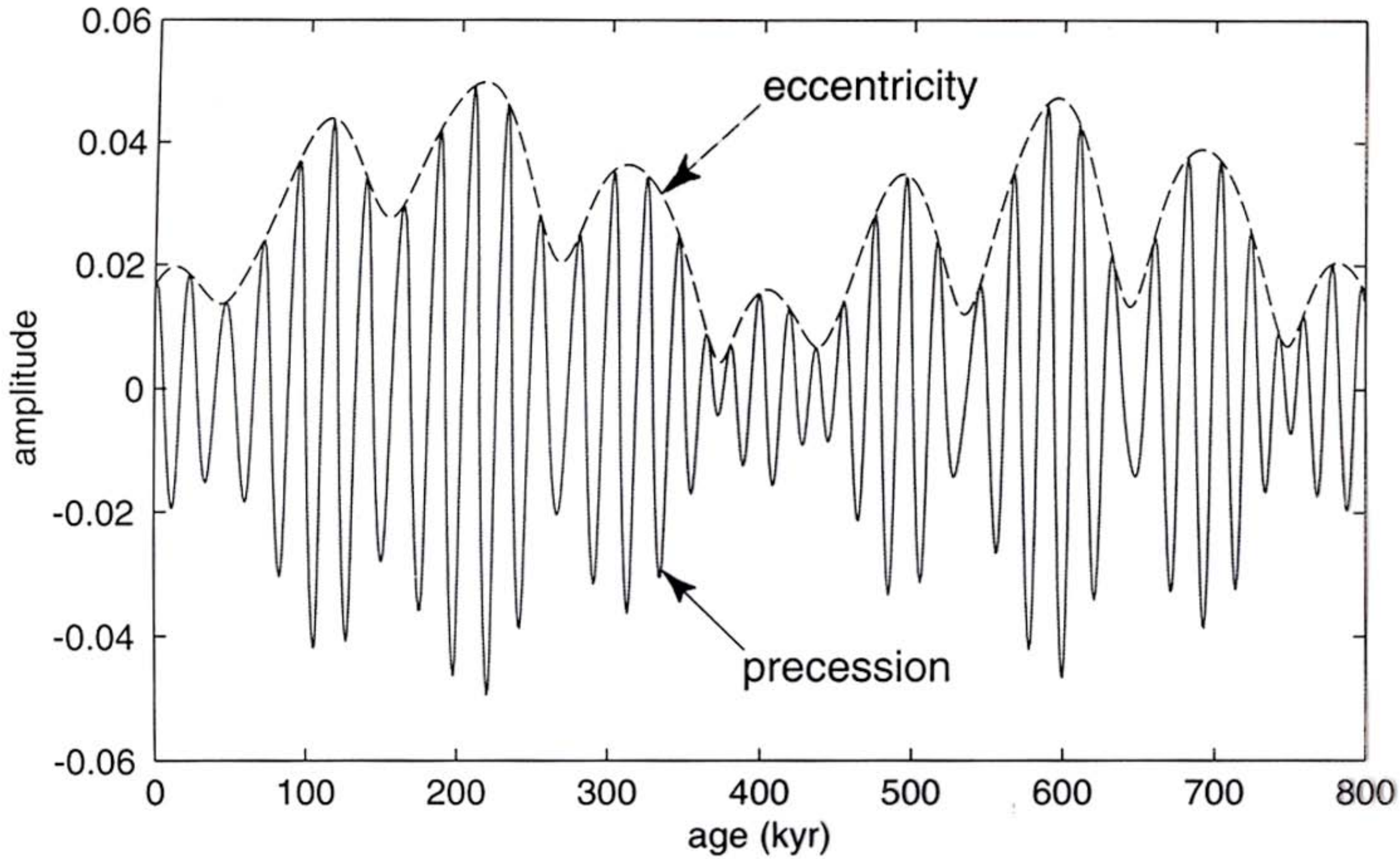


Precession influence on climate: why 23,000 years not 25,800?



Earth's axis has precessed 22/26 of a cycle, and the eccentricity of the orbit has precessed "backwards" 4/26 of a cycle, bringing us back to a configuration which is equivalent in terms of radiation

Eccentricity amplitude-modulates precession



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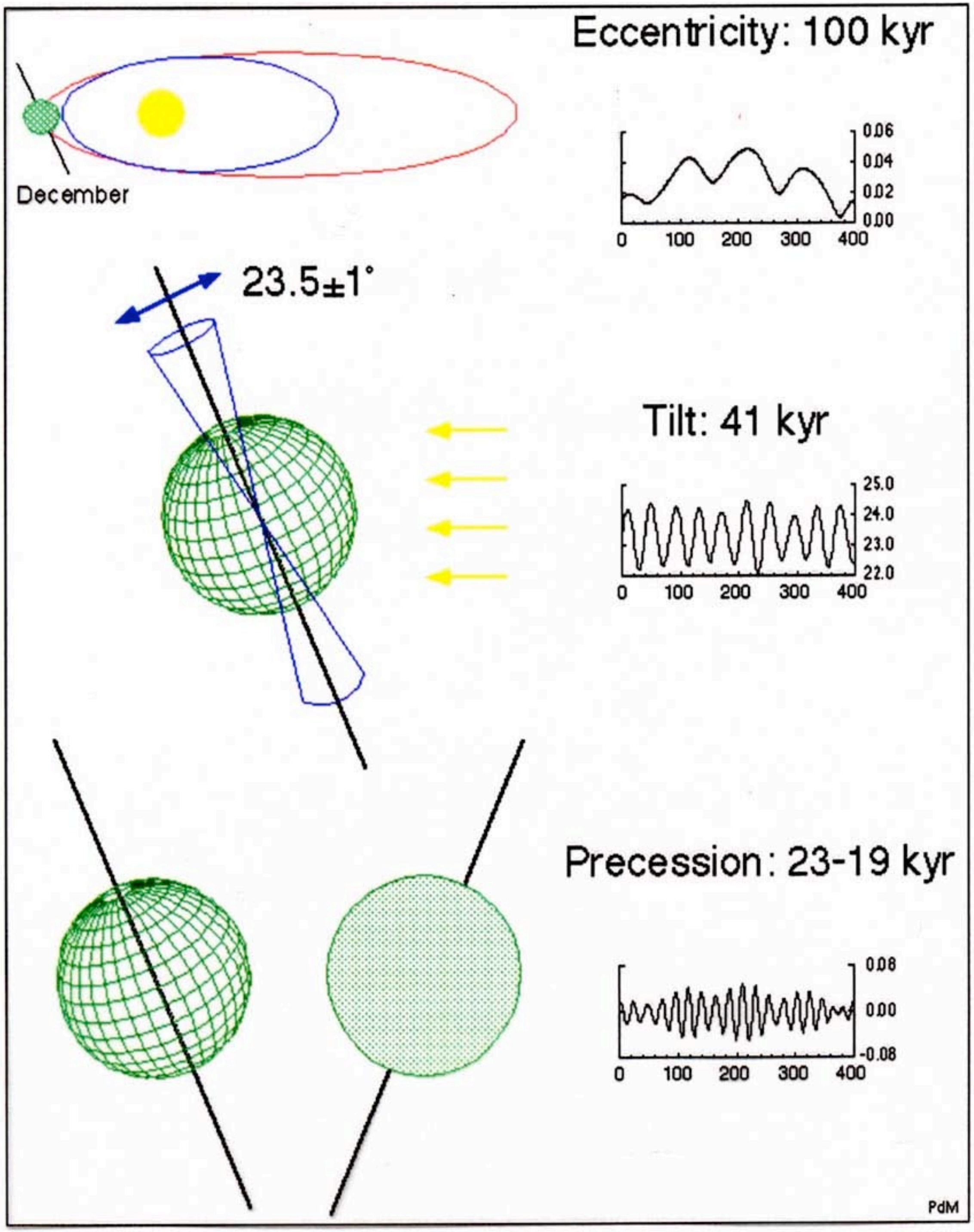
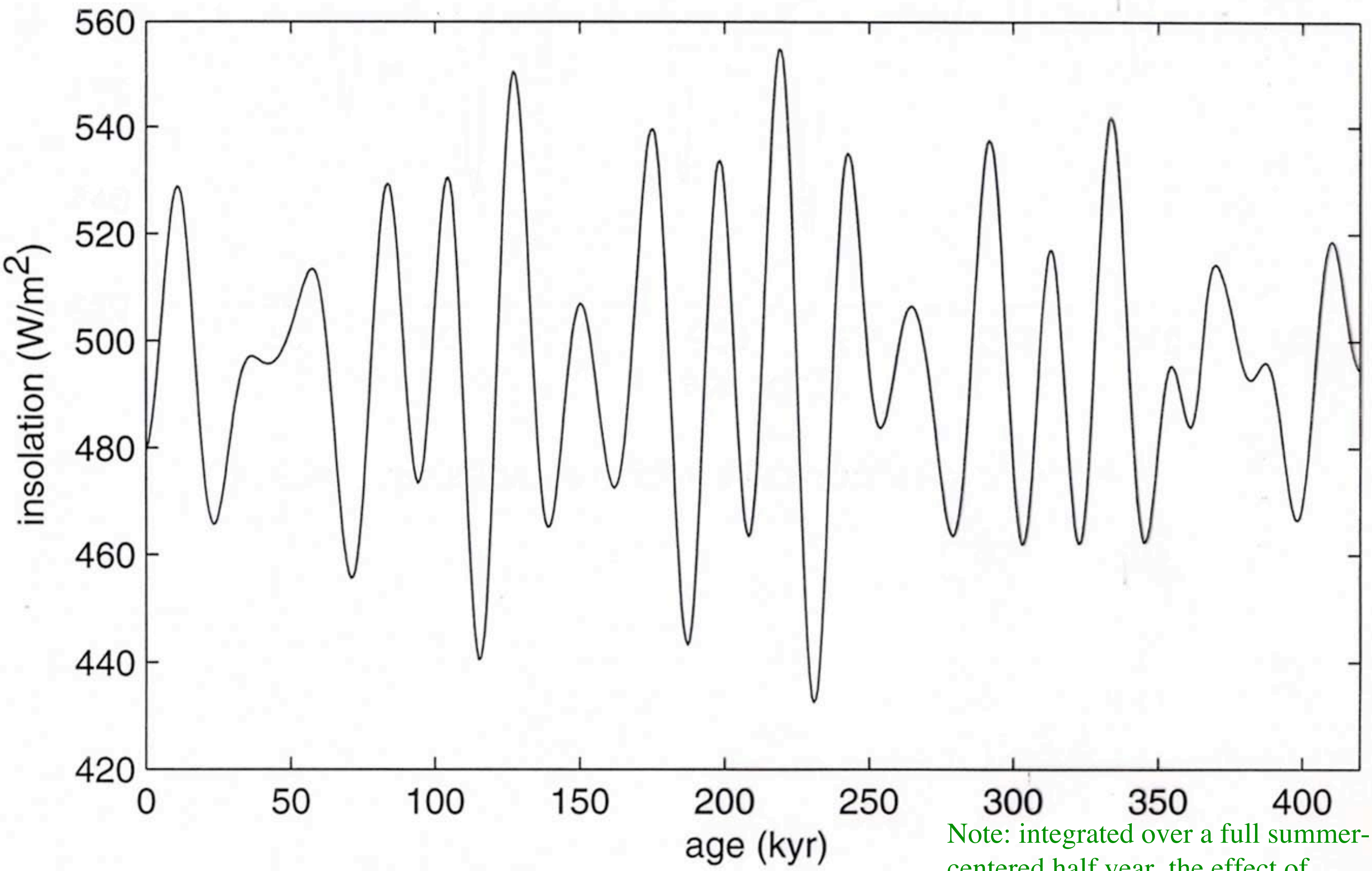


Periodic changes in orbital geometry modulate solar radiation receipts (insolation)

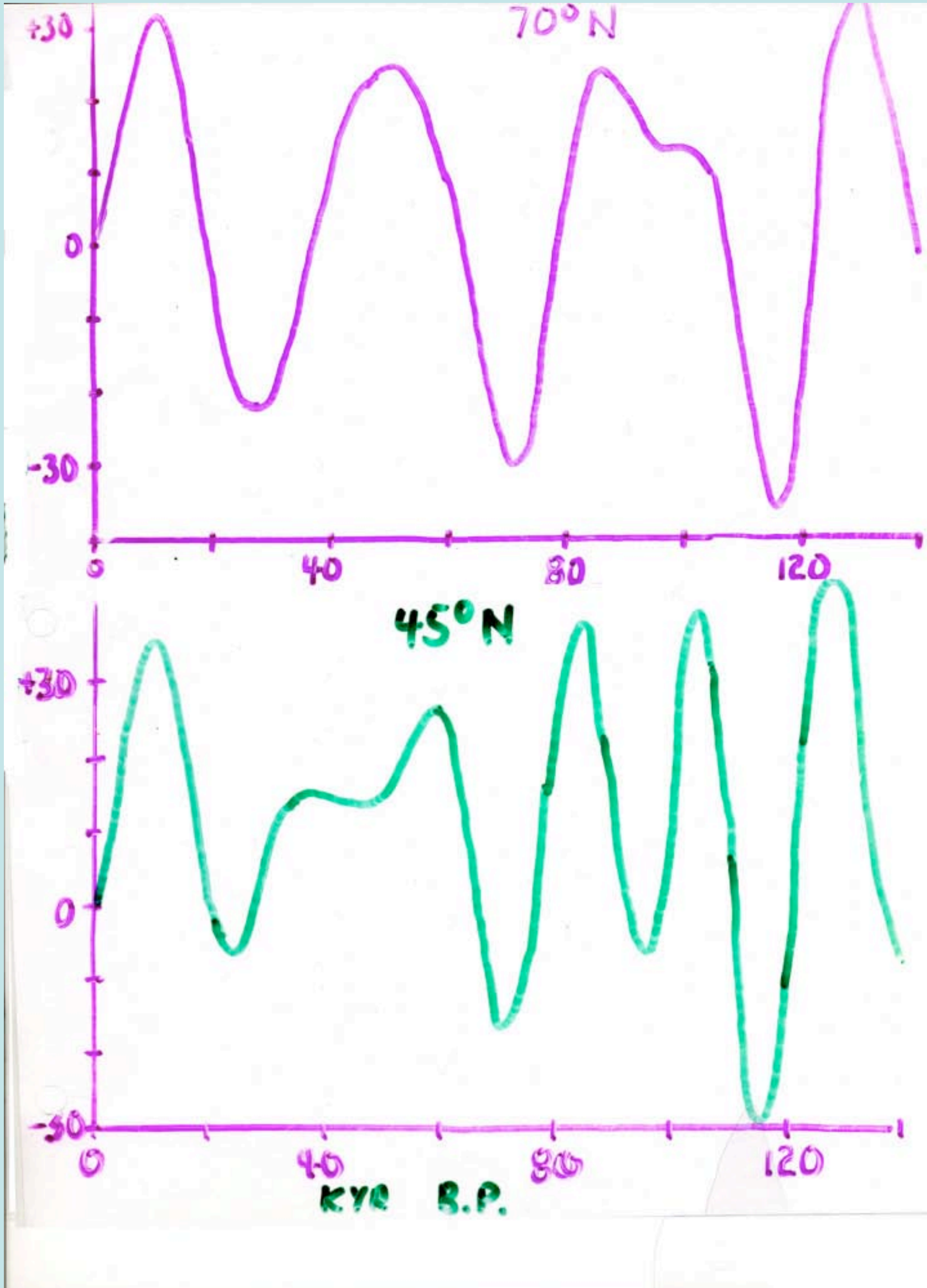
Insolation at 65°N, June 21



Insolation, July 65N.

Note: integrated over a full summer-centered half year, the effect of obliquity is much stronger than in this single-day series

Summary half-year insolation, cal/cm²/day



Integrated over a half-year centered on summer, obliquity dominates high latitude insolation and precession dominates lower latitude insolation

Did increasing Northern Hemisphere summer insolation cause the end of the last ice age?

Milankovitch Hypothesis: Milestones & Support

- Kullenberg (1947): Invented deep-sea piston coring.
  →Recovery of long, continuous climate records possible.

- Emiliani (1955): Pioneered use $^{18}O/^{16}O$ ratio of fossil foraminifera in sediment cores as climate (temp.) proxy.

- Olausson (1965); Shackleton (1967): Interpret foram $\delta^{18}O$ changes as whole-ocean isotopic shifts caused by ice sheet growth/decay.

- 1960's: Recognition of magnetic stripes on ocean floor (geomagnetic field reversals) as global stratigraphic markers.

- Johnson (1982); Shackleton et al (1990): Use astronomically-driven insolation variations (E, T, P) to derive timescales for deep-sea cores.
  →Accurately predict age of Brunhes-Matuyama (B/M) magnetic reversal, 780-790 kyr BP. (K/Ar dates for B/M incorrectly placed it at 730 kyr BP.)

- Baksi et al (1992): $^{40}Ar/^{39}Ar$ date for B/M = 783 kyr BP.

- Raymo (1997): Multiple $\delta^{18}O$ records on 'simple' timescale supports link between N. Hemisphere summer insolation and glacial terminations.

→Strong support for astronomical influence on climate. (The magnitude of which remains debated…)

Absolute chronology and its importance to testing the Milankovitch Hypothesis

- Carbon-14 dating: 0-25 kyr BP (where reliable “initial C14” calibrations exist)

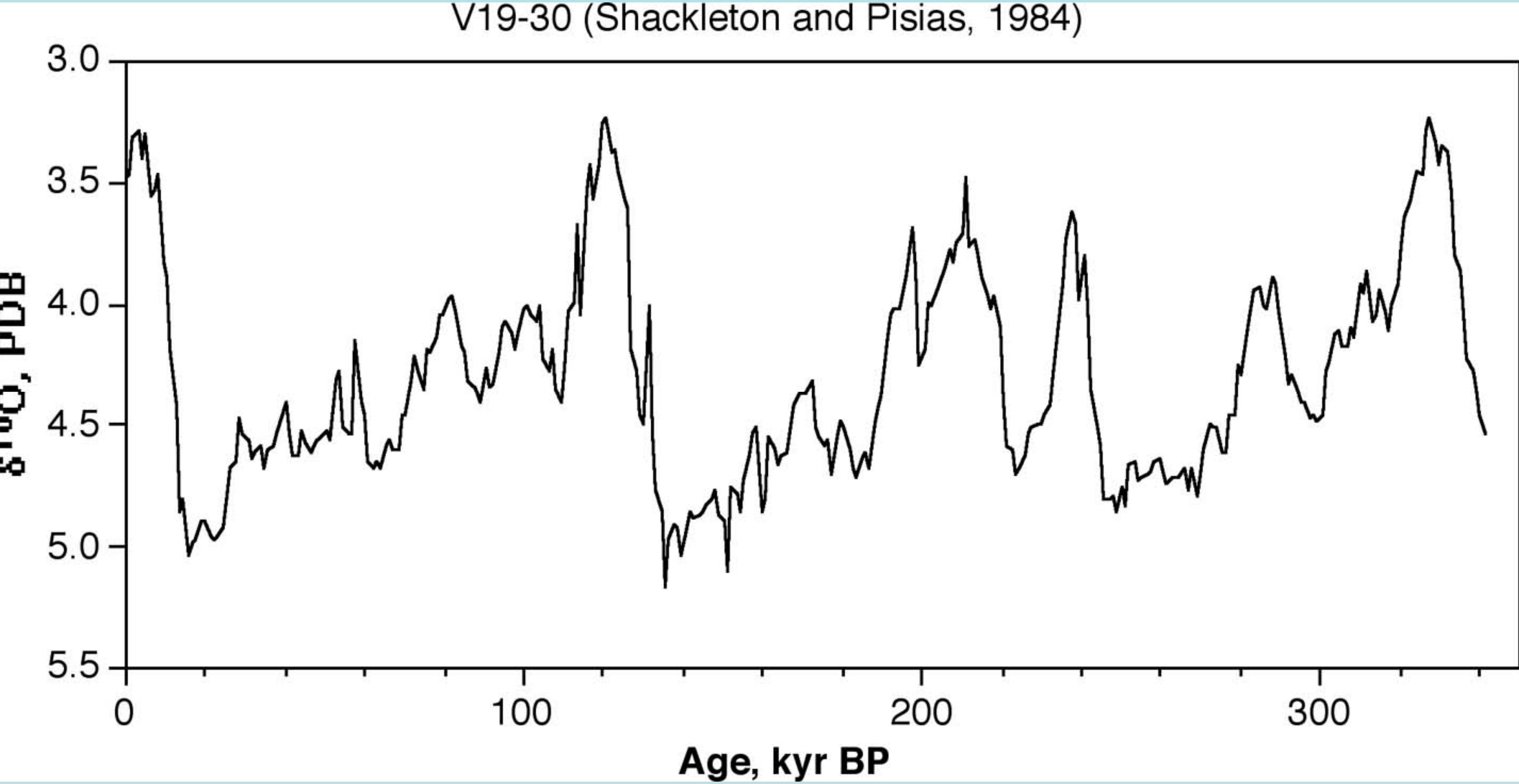
- Layer counting in sediments and ice cores: 0-40 kyr BP varves, density bands, annual dust cycles (but do you miss some bands or see two where only one should be?)

- ^{234}U -> ^{230}Th ingrowth in corals and speleothems: 0-250,000 kyr BP

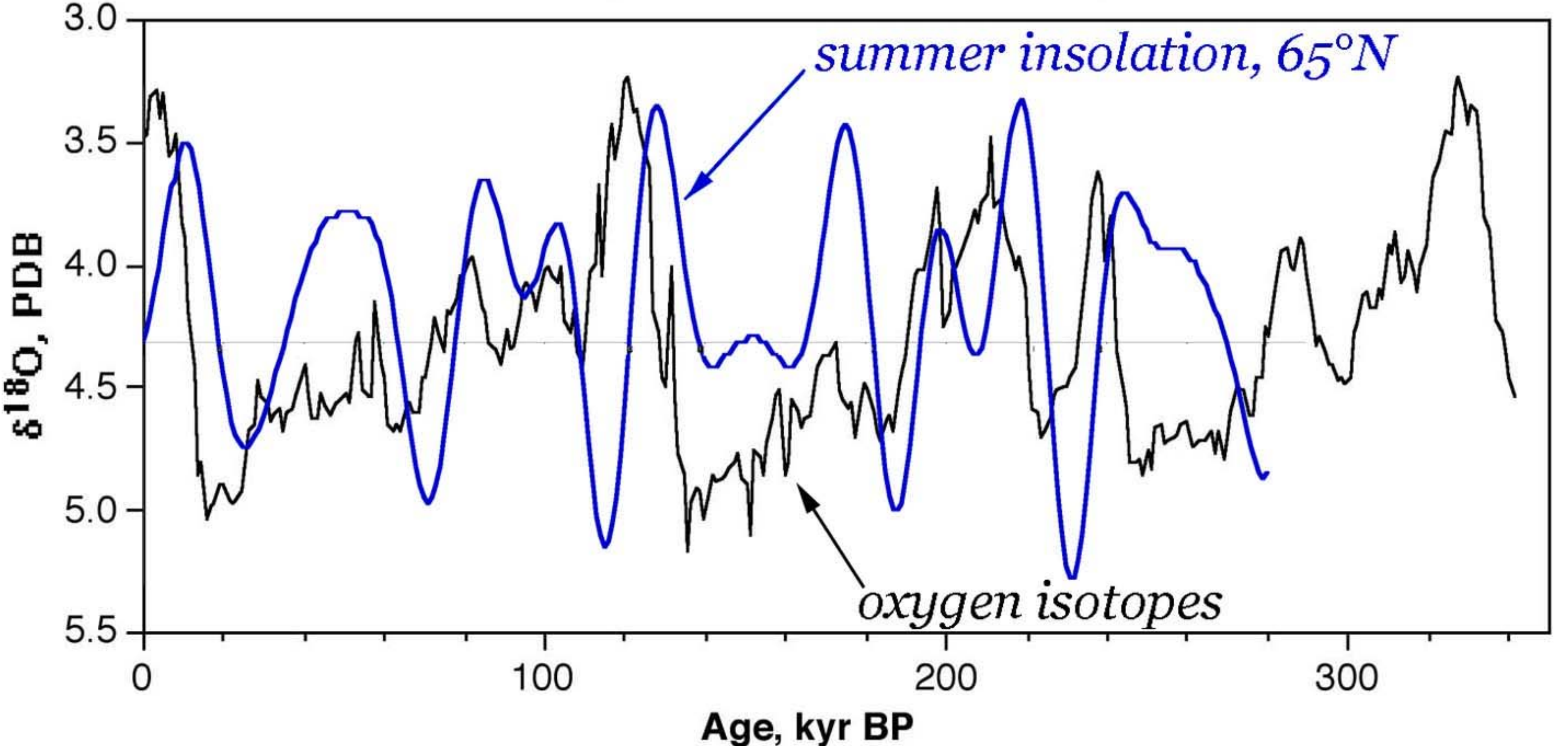
- ^{40}K -> ^{40}Ar dating of basalts at magnetic reversals

How do we estimate a time scale for a marine sediment core or ice core?

- We measure depth and assume it is an increasing function of the age of the deposit (stratigraphy).
- For sediments <25 kyr BP containing appropriate carbonate or organic) fossils, we can measure the ^{14}C content and determine the age from the atmospheric radicarbon calibration.
- We can determine the $\delta^{18}O$ of carbonate fossils and correlate the features to sea level events of known age (from ^{230}Th-^{234}U dating).
- For sediments with appropriate magnetic minerals, we can measure the magnetic alignment and determine the position of known ($^{40}Ar/^{39}Ar$ dated) magnetic reversals.
- In-between these known dates, we must interpolate using some plausible (but unprovable) scheme.


V19-30 (Shackleton and Pisias, 1984)
3.0
3.5
4.0
4.5
5.0
5.5
δ18O, PDB
0
100
200
300
Age, kyr BP

Oxygen isotopes compared to summer insolation at 65°N



SPECMAP stack. Note terminations (rapid deglaciations)

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Citation: Figure 5. Berger, Andre L. *Milankovitch and Climate*. Kluwer Academic Publishers, June 1984, 544 pages. ISBN: 902771777X.

Milankovitch Hypothesis Challenges:

100-kyr Cycle Problems

1. Why is climate response in 100-kyr band so strong?

   Observation: High correlation of $\delta^{18}O$ cycles with astronomically-driven radiation cycles at E, T & P frequencies suggests causal link in all 3 bands.

   Problem: Amplitude of insolation change (~0.2%) is ~10x smaller than in T,P bands.

   Possible Solution: E modulates climatic effect of P. High E favors NH glaciation when P causes NH summer to occur at maximum Earth-Sun distance (i.e., Imbrie et al, 1993).

2. Why do glacial cycles switch from 41-kyr to 100-kyr period ~700 kyr BP?

   Possible solution: L/T cooling trend, perhaps from tectonically-driven decrease in atmospheric CO_2, facilitates NH ice sheet growth beyond a critical threshold during insolation minima. These large ice sheets drive climate through feedbacks internal to the climate system (geo-, cryo-, atmo-, hydro-sphere).

3. Why do full glacial Terminations, and ensuing interglacial periods, occur ~430 and ~15 kyr BP when E is very low?

   -*Possible solution:* 100-kyr cycle of orbital inclination (Muller and MacDonald, 1995).

   -*Caveat:* no obvious mechanism linking climate to inclination.

Pleistocene Ice Age Cycles

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Citation: Raymo, M. E., W. F. Ruddiman, N. J. Shackleton, and D. W. Oppo.
Evolution of Atlantic-Pacific $\delta\,^{13}C$ *gradients over the last 2.5 m.y*. EPSL 97 (1990): 353-368.

Earth's orbit also oscillates in and out of orbital plane every ~100 kyr:

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Citation: Muller and MacDonald. *Nature* 377 (1995): 107-108.

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