The Ice Ages
• The Ice Ages lasted 2.7 Myr BP to about 10,000 yrs ago

• Large Ice sheets covered Northwestern Europe and Northern North America
• Due to orbitally induced changes in northern hemisphere summer insolation
  – Ice volume changes are coordinated with CO₂ changes (shift of carbon between atmosphere and oceans)

Brief History of Orbital Theory of the Ice Age Cycles
• Agassiz (1840)
  – Summarized geologic evidence for an ice age
• Adhemar (1842)
  – First to attribute ice age to orbital changes of Earth around Sun
  – Highlighted precession and # of hours of daylight
• Croll (1864)
  – Postulated winter was key; high eccentricity & winter hemisphere near aphelion promoted ice accumulation
  – Theory dropped when prediction of timing of glacial conditions didn’t match evidence
• Milankovitch (1911)

Milankovitch (1911)
• Koppen suggested to M. that summer insolation was the key to the ice ages
  – Winter: too cold to get much accumulation
  – Summer: low-insolation summers produce less melt in Fall and Spring, allowing winter snow to persist.
• M. calculated summer insolation at 65N vs time
• At the time, proxy data did not support predicted timing of glacial vs interglacial conditions
• New data from ocean sediment cores (and new data methods) clearly showed the ice ages went in cycles, and matched pretty well with summer insolation at 65N

Orbital Theory: Trigger and Feedback Mechanism

- Ice-albedo feedback
  - Global mean temperature
  - Intensity of summer insolation at high northern latitudes

- Planetary albedo
- Growth of continental ice sheets

Trigger with feedback causes ice-sheets...
- to grow and keep growing
- or to melt and keep melting

- Other feedbacks are needed to explain the magnitude of the changes.
- Greenhouse gases (e.g. CO₂ and CH₄) seem to be involved.

Orbital Variations and Insolation

Obliquity or Tilt

- Tilt angle is presently 23.5°
- Tilt is a big reason why we have large seasonal cycles in mid-latitudes and polar regions
- Variations in tilt angle have no impact on global average insolation
Summary: orbital changes on insolation

- Amplitude of the seasonal cycle of TOA insolation:
  - For reference, today the seasonal cycle is +/- 150 Wm$^{-2}$ in the midlatitudes, and +/- 15 Wm$^{-2}$ in the tropics
  - The net effect of orbital changes on seasonal insolation is +/- 30 Wm$^{-2}$ in the midlatitudes, and +/-20 Wm$^{-2}$ in the tropics.
  - Precession (23kyr) dominates in the tropics; Precession and tilt (41kyr) affect the high latitudes
- Note that overall, insolation changes are larger in the extratropics than in the tropics, but the latter may also have a large impact on climate.
- Tilt and precession cause summer insolation changes that are out of phase with winter insolation changes (double whammy on ice volume).
- Only eccentricity can change the global, annual average insolation (by about .18%, or 5 Wm$^{-2}$).

The ice volume time series

- Composite stack of many $\delta^{18}$O deep sea cores (~20)

Imbrie et al., 1984
The ice volume time series

June insolation at 65N (upside down)

- maximum correlation of -0.4 with a 6 kyr lag of ice volume behind insolation
- more ~100 kyr variability in ice volume than in insolation

Rate of change of ice volume

- Rate of change of ice volume more directly related to high latitude insolation
- maximum correlation of -0.8 at zero lag

Rate of change of ice volume

- Terminations coincide with insolation maxima - points to insolation trigger
- Major difference is large negative rates of change during major deglaciations

Ice Age Cycles: Some big solved problems

- Current climate is not the only possible one for Earth – indeed, glacial conditions seem to be preferred for the past 3Myr
- The ice Age Cycles wax and wane due to changes in the way the Earth Orbits the sun
  - Global climate and CO₂ are intimately intertwined
  - but CO₂ is acting as a feedback and not the driver of ice age cycles
- A change in global-mean surface temperature of about 5°C is a massive climate shift
- If the orbital parameter theory is right, small triggers can produce major climate changes under some conditions

Ice Age Cycles: Some big unsolved questions

- Why is CO₂ so highly correlated with ice volume?
The Ice Age Cycles: Some big unsolved questions

- Why is CO$_2$ so highly correlated with ice volume?

- Are changes in CO$_2$ fundamental for ice ages, or do they provide a weak positive feedback?
  - Is ice volume in the northern hemisphere correlated with ice volume in the southern hemisphere throughout the ice ages?

- What causes the major deglaciations?
  - Much more ice is lost in the terminations of an ice age than would be expected by simple increases in insolation.