Wed. Feb. 28, 2018

• Reminder: Midterm exam next Wednesday
  – Closed book, Closed Notes
  – Do bring a calculator
  – Review session Monday

• Today:
  – Finish Thermal Remote Sensing Pt. 1 (IR emission)
    • Use Monday's posted slides

• Today + Friday:
  – Thermal Remote Sensing Pt. 2 (Heat transfer)
    • New slides posted for today

• Tomorrow at ~3PM MST: Launch of GOES-S
  – NASA TV or <http:www.spaceflightnow.com>
GOES-S Launch Tomorrow

- 2nd of 4 in upgraded “GOES-R” series
  - First GOES-R (now GOES-16) launched Nov. 2016
  - Will be renamed GOES-17 once in operation
  - To be positioned at 137° W Long. (Pacific Coast)
    - GOES-16 is positioned off East Coast
  - 15 year expected life
- Geosynchronous (equatorial) satellites like this launch from Cape Canaveral
  - (POES launch from Vandenberg on W. Coast)
  - 2 hr launch window opens as 3:02 MST
  - Coverage on NASA TV and <http://spaceflightnow.com>
Use slides posted Monday for first part (Thermal Emission)
Heat Transfer -- Today and Friday

• Thermal Remote Sensing Part 2.
  – Review -- emissivity effects
  – Temperature changes:
    • conductivity, heat capacity, diffusivity
    • thermal inertia
  – Geological Examples

– Heat loss studies
Heat Transfer

• Heat Transfer (more quantitative than Sabins)
  – Properties which control how material heats up and cools down:
    • Conductivity
    • Heat Capacity
    • Density
    • (Also albedo -- since it controls absorption of sunlight)

  – Derived terms:
    • Thermal Inertia
    • Thermal Diffusivity
    • Apparent thermal inertia
Lunar Eclipse
Measurements of Thermal Inertia

Visible image of full moon
Infrared (MSX) image in eclipse

Most of moon cools quickly: Low thermal inertia \((kpc)^{1/2}\) \(\Rightarrow\) porous regolith
Around craters is cools slowly: High thermal inertia \(\Rightarrow\) exposed bare rock
Thermal Constants: Conductivity

- Heat flow \( q \): \( \text{W/m}^2 \)

\[
q = -K \frac{dT}{dz}
\]

where \( K = \text{Thermal Conductivity} \) \((\text{W/m}^2)/(\text{K/m}) = \text{W m}^{-1} \text{K}^{-1}\)

book uses “older” units of \( \text{cal cm}^{-1} \text{ sec}^{-1} \text{oC}^{-1} \)
Thermal Constants: Conductivity

Suppose diagram represents $T=300K$ surface at top, $T=1300K$ molten lava at base, with 0.1 m thick crust of basalt between.

$$q = -K \frac{dT}{dz} = -2.1 \text{ W m}^{-1} \text{ K}^{-1} \frac{1000 \text{ K}}{0.1 \text{ m}} = -21,000 \text{ W m}^{-2}$$

Basalt:
$$K = 0.0050 \text{ cal cm}^{-1} \text{ sec}^{-1} \text{ oC}^{-1} \times 4.187 \text{ J/cal} \times 102 \text{ cm/m} = 2.1 \text{ J s}^{-1} \text{ m}^{-1} \text{ K}^{-1} = 2.1 \text{ W m}^{-1} \text{ K}^{-1}$$

• A shoe sole is $\sim 10 \text{ cm} \times 30 \text{ cm} = 0.1 \text{ m} \times 0.3 \text{ m} = 0.03 \text{ m}^2$ so a sole would absorb $21,000 \text{ W m}^{-2} \times 0.03 \text{ m}^2 = 630 \text{ W}$. Will get warm – but can stand it for short time.
Heat Capacity

C: Heat Capacity  (Thermal Capacity)  
\[ J \text{ kg}^{-1} \circ C^{-1} \]

Basalt:
\[ C = 0.20 \text{ cal g}^{-1} \circ C^{-1} \]
\[ \times 4.187 \text{ J/cal} \times 1000 \text{ g/kg} \]
\[ = 840 \text{ J kg}^{-1} \text{ K}^{-1} \]

To get heat capacity of unit volume, find \( \rho C \) where
\[ \rho = \text{density} = 2.8 \text{ g cm}^{-3} \]
\[ \times (10^2 \text{ cm/m})^3 / (10^3 \text{ g/kg}) \]
\[ = 2800 \text{ kg m}^{-3} \]

\[ \rho C = 840 \text{ J kg}^{-1} \text{ K}^{-1} \times 2800 \text{ kg m}^{-3} \]
\[ = 2.3 \times 10^6 \text{ J m}^{-3} \text{ K}^{-1} \]
Heating time?

Have 1 meter on a size block, with heat flowing into it as given in previous example: \( q = 21,000 \text{ W m}^{-2} \)

Heat capacity per unit volume is

\[ \rho C = 2.3 \times 10^6 \text{ J m}^{-3} \text{ K}^{-1} \]

Volume is 1 m\(^3\) so total heat capacity is \( 2.3 \times 10^6 \text{ J K}^{-1} \)

Total heat flow is 21,000 W = 21,000 J s\(^{-1}\) since area \( A = 1 \text{ m}^2 \).

Heating rate will be

\[ 2.1 \times 10^4 \text{ J s}^{-1} / 2.3 \times 10^6 \text{ J K}^{-1} = 0.91 \times 10^{-2} \text{ K s}^{-1} \sim 10^{-2} \text{ K s}^{-1} \]

Heating rate was proportional to
\[ q/\rho C \propto K/(\rho C) \]

Define \( k = K/(\rho C) \) as “Thermal Diffusivity”

\[ k = 2.1 \text{ W m}^{-1} \text{ K}^{-1} / 2.3 \times 10^6 \text{ J m}^{-3} \text{ K}^{-1} = 9.1 \times 10^{-7} \text{ m}^2 \text{ s}^{-1} \text{ for basalt} \]
Thermal Diffusivity

\[ \frac{\partial T}{\partial t} = \frac{K}{\rho C} \frac{\partial^2 T}{\partial x^2} \]

How far does thermal wave propagate in given \( \Delta t \)?
Assume given \( \Delta T \), solve for \( \Delta x \):
\[ \frac{\Delta T}{\Delta t} = \frac{K}{\rho C} \frac{\Delta(\Delta T)}{(\Delta x)^2} \]
\[ \Delta x = \sqrt{\frac{K}{\rho C} \Delta t} \]

For basalt \( k = 9 \times 10^{-7} \text{ m}^2 \text{ s}^{-1} \)

If you wait 1 year = \( 3.15 \times 10^7 \text{ s} \), how far does thermal wave propagate?
\[ \Delta x = (9 \times 10^{-7} \text{ m}^2 \text{ s}^{-1} \times 3.15 \times 10^7 \text{ s})^{\frac{1}{2}} = (28 \text{ m}^2)^{\frac{1}{2}} = 5.3 \text{ m} \]

With sandy soil \( k = 3 \times 10^{-7} \text{ m}^2 \text{ s}^{-1} \) so
\[ \Delta x = (3 \times 10^{-7} \text{ m}^2 \text{ s}^{-1} \times 3.15 \times 10^7 \text{ s})^{\frac{1}{2}} = (9.4 \text{ m}^2)^{\frac{1}{2}} = 3.1 \text{ m} \]

If you wait 1 day = \( 8.6 \times 10^4 \text{ s} \), how far does thermal wave propagate in sandy soil?
\[ \Delta x = (3 \times 10^{-7} \text{ m}^2 \text{ s}^{-1} \times 8.6 \times 10^4 \text{ s})^{\frac{1}{2}} = (2.6 \times 10^{-2} \text{ m}^2)^{\frac{1}{2}} = 0.16 \text{ m} \]
Periodic Heating of Surface

If you solve heat conduction equation for the case where
\( F = F_0 \cos(\omega t) \) is net heat flux through surface

\[
T = \frac{F_0}{P \sqrt{\omega}} \cos(\omega t - \frac{\pi}{4}) + T_0
\]

will be surface temperature.

where \( P = \sqrt{K \rho C} = \text{Thermal Inertia} \)  (most people use symbol \( \gamma \), not \( P \))

So amplitude of T variation is \( \propto \frac{F_0}{(P \omega^{1/2})} \)

Large thermal inertia \( \Rightarrow \) small T variation

**Figure 5-6** Effect of differences in thermal inertia on surface temperatures during diurnal solar cycles. Note differences in \( \Delta T \) for materials with high and low thermal inertia.

A. Solar heating cycle.

B. Variations in surface temperature.

Sabins Fig. 5-6

Note – figure is badly oversimplified.

T should really be delayed in phase

Also, **NET** flux is not sinusoidal.
For Basalt
\[ P = \sqrt{K\rho C} = \sqrt{2.1 \text{ W m}^{-1} \text{ K}^{-1}} \times 2800 \text{ kg m}^{-3} \times 840 \text{ J kg}^{-1} \text{ K}^{-1} \]
\[ = 2.2 \times 10^3 \text{ J m}^{-2} \text{ K}^{-1} \text{ s}^{-1/2} \]

If the net flux varied by 500 W m\(^{-2}\) (about 1/3 \(F_{\text{sun}}\))

and the frequency \(\omega = \frac{2\pi}{1 \text{ day}} = \frac{2\pi}{8.64 \times 10^4 \text{ s}} = 7.27 \times 10^{-5} \text{ s}^{-1}\)

then we would expect a temperature variation of
\[ F_0 = \frac{500 \text{ W m}^{-2}}{P \sqrt{\omega}} = \frac{500 \text{ W m}^{-2}}{2.2 \times 10^3 \text{ J m}^{-2} \text{ K}^{-1} \text{ s}^{-1/2} \sqrt{7.27 \times 10^{-5} \text{ s}^{-1}}} = 26 \text{ K} \]
Remote Determination of Thermal Inertia

- Despite what book says, you really can determine P remotely if you have \((1-A) \times F_{\text{sun}}(t)\) and \(T(t)\).

\[
P = 3 \times 10^4 \text{ erg cm}^{-2} \text{ s}^{-1/2} \text{ K}^{-1}
= 3 \times 10^{-3} \text{ J cm}^{-2} \text{ s}^{-1/2} \text{ K}^{-1}
= 7.2 \times 10^{-4} \text{ cal cm}^{-2} \text{ s}^{-1/2} \text{ K}^{-1}
\]

Text quotes sandy soil as 0.050 (\(= 5 \times 10^{-2}\)) cal cm\(^{-2}\) s\(^{-1/2}\) K\(^{-1}\)
so Ganymede resists \(T\) changes 100 \(\times\) worse.

\[
P = (K \rho C)^{1/2}
\]
If change is due to \(K\), it is 10000 \(\times\) smaller, due to pulverized regolith

**Fig. 2.**—Radiometry of Ganymede compared with predicted 20-\(\mu\) fluxes. *Filled circles*, measurements of Ganymede with sample estimated error bars indicated. *Open circles*, observations of Callisto (J IV). *Solid curve*, the prediction of the best-fitting homogeneous model, for which the thermal inertia is \(3 \times 10^4\) ergs cm\(^{-2}\) s\(^{-1/2}\) K\(^{-1}\).
Summary: Material Terms

- **$K$** - Thermal conductivity
  - How well material conducts heat

- **$C$** - Heat capacity
  - How much energy is stored

- **$\rho$** - Mass per unit volume

- **$A$** - Albedo
  - Fraction of sunlight reflected

- **$\kappa = k = \frac{K}{\rho C}$** - Thermal diffusivity
  - How fast thermal wave travels

- **$\gamma = P = \sqrt{K\rho C}$** - Thermal Inertial
  - How well surface resists T changes

- **$\text{ATI} = \frac{1-A}{\Delta T}$** - Apparent Thermal Inertia
  - Simple observational measure of thermal inertia
Summary: Material Terms

- **$K$**: Thermal conductivity
  
  How well material conducts heat

- **$C$**: Heat capacity
  
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- **$\rho$**: Mass per unit volume

- **$A$**: Albedo
  
  Fraction of sunlight reflected

- **$\kappa = k = \frac{K}{\rho C}$**: Thermal diffusivity
  
  How fast thermal wave travels

- **$y = P = \sqrt{K\rho C}$**: Thermal Inertial
  
  How well surface resists $T$ changes

- **$ATI = \frac{1-A}{\Delta T}$**: Apparent Thermal Inertia
  
  Simple observational measure of thermal inertia
Typical Thermal Properties

Thermal diffusivity: Distance of propagation of thermal wave in time \( \Delta t \)?

\[
\Delta x = \sqrt{\frac{K}{\rho C}} \Delta t
\]

For sandy soil and \( t = 1 \) day = \( 8.6 \times 10^4 \) s

\[
\Delta x = (3 \times 10^{-7} \text{ m}^2 \text{ s}^{-1} \times 8.6 \times 10^4 \text{ s})^{1/2} = (2.6 \times 10^{-2} \text{ m}^2)^{1/2} = 0.16 \text{ m}
\]

Thermal inertia: Degree of resistance to temperature change

For Basalt

\[
P = \sqrt{K \rho C} = \sqrt{2.1 \text{ W m}^{-1} \text{K}^{-1} \times 2800 \text{ kg m}^{-3} \times 840 \text{ J kg}^{-1} \text{ K}^{-1}} = 2.2 \times 10^3 \text{ J m}^{-2} \text{ K}^{-1} \text{ s}^{-1/2}
\]

Amplitude of \( T \) diurnal variation

\[
\approx \frac{F_0}{P \sqrt{\omega}} = 26 \text{ K}
\]

(so \( \Delta T = 52 \text{ K} \), probably an overestimate if we include atmospheric cooling, etc.)
Thermal Inertia and diurnal cycle

Sabins Fig. 5-7

\[ F_{\text{net}} = (1-A) F_{\text{sun}} - \sigma T^4 \]
where \( A = \text{Albedo} \)

Wet soil has higher thermal conductivity so higher thermal inertia, but it and vegetation are also affected by evaporation, which limits temperature rise.

Figure 5-7 Diurnal radiant temperature curves (diagrammatic) for typical materials.
Crossover times for two materials

Figure 5-7 Diurnal radiant temperature curves (diagrammatic) for typical materials.
How far does thermal wave propagate in given $\Delta t$?
Assume given $\Delta T$, solve for $\Delta x$:

$$\Delta x = \sqrt{\frac{K}{\rho C}} \Delta t$$

$= 0.16 \text{ m}$ in sandy soil in 24 hr.

Gravel and windblown sand conceal bedrock. Cover thinner than diurnal skin depth.
Gravel and windblown sand conceal bedrock. Cover thinner than diurnal skin depth.
Aerial Photo and Night Thermal Imagery, Indio Hills

Palm Springs Formation: alternating beds of resistant conglomerate sandstone and nonresistant siltstone

Ocotillo Conglomerate: Poorly stratified

Vegetation

Alluvium

Cool:

Alluvium?

Damp?

Shadows?

Syncline and Anticline

Figure 5.19: Images of the geology section of the Indio Hills, California. From Sabins (1967).
Thermal Images: Stilfontein

Sabins Fig. 5-25 pg. 160
Aerial Photo, Nighttime IR, Interpretation
Stilfontein, South Africa

Dark linear features: Faults and joints filled with moist soil

Dolomite: Warm (bright) High $\rho$ and Thermal Inertia
Chert-Rich beds: Cool (dark) Low $\rho$ and Thermal Inertia
Apparent Thermal Inertia

• Simplified version is often used in terrestrial remote sensing:

\[ \text{ATI} = \frac{1 - A}{\Delta T} \]

where \( \Delta T = T_{\text{max}} - T_{\text{min}} \)

• Works because \( F_{\text{sun}} \) is roughly similar “everywhere” on Earth

• Can make an “ATI” image from a visible image (to get A) and a day and a night thermal image (to get \( T_{\text{max}} \) and \( T_{\text{min}} \).
ATI Derivation for San Rafael Swell, Utah

\[
\text{ATI} = \frac{1 - A}{\Delta T}
\]

Figure 5-33 Enlarged HCMM images of the San Rafael Swell, Utah. From Kahle and others (1981). Courtesy A. B. Kahle, Jet Propulsion Laboratory.
Sabins Fig. 5-33d and 5-34
Urban Heat Loss

Figure 5-17 Heat-loss survey of Brookhaven National Laboratories, Long Island, New York. Localities are explained in the text. Courtesy Daedalus Enterprises, Inc.

Sabins Fig. 5-17
Mars “TES” Results

**TES Andesite Abundance**

**TES Basalt Abundance**
TIMS: Cuprite Hills, NV

Figure 5-37  Thermal IR spectra of rocks and minerals. Spectra are offset vertically. From Kahle (1984, Figure 4).

Sabins: TIMS image showing bands 3, 2, 1 as RGB
TIMS: Cuprite Hills, NV

Sabins: TIMS image showing bands 3,2,1 as RGB, then image showing emissivity variations.
C. TIMS image showing emissivity information, Cuprite Hills, Nevada.

**Figure 5-38** Interpretation map of TIMS images of the Cuprite Hills, Nevada. From Hook and others (1992, Figure 5).

Sabins: TIMS emissivity image and map