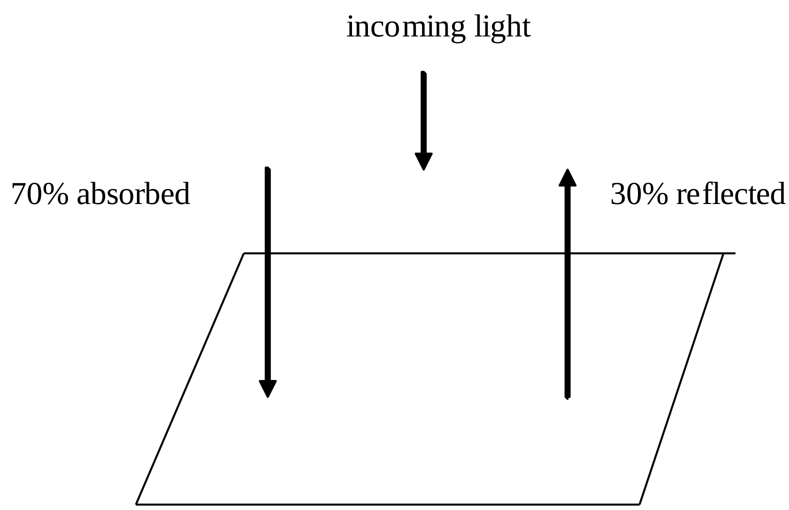
Solar System Temperatures

50 cent words not in the text's glossary

Bond albedo

The Bond albedo is the fraction of power in the total electromagnetic radiation incident on an astronomical body that is reflected back out into space. It takes into account all wavelengths and all possible angles Sun-object-observer. While the definition is simple, the measurement is not, and must be done from a spacecraft as all the angles are not available from Earth. Example:



Bond albedo = 0.3

Stefan's Law

$$F = (\text{Stefan} - \text{Boltzmann constant})\,T^4$$

where

F is the flux, or power in Watts per square meter of surface emitted by a blackbody,

the Stefan-Boltzmann constant $= 5.67040 \times 10^{-8}\, W\, m^{-2}\, K^{-4}$

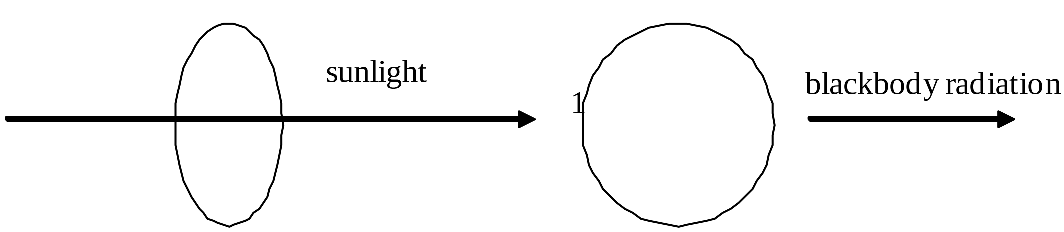
T is the temperature in degrees Kelvin.

Power of the Sun

The Sun is a good approximation to a blackbody. The solar constant is the total power of the Sun at a distance of 1 AU (the average distance between the Sun and the Earth). The measured value is S = 1367.6 W m^{-2}. This quantity varies by less than 0.1% during the solar sunspot cycle, and will be taken as constant.

Steady state temperatures

Suppose a spinning spherical blackbody of radius R positioned 1 AU from the Sun. Sunlight passing through a circle of radius R and area πR^2 hits the blackbody and is absorbed. Blackbody radiation is emitted over the entire surface area, $4 \pi R^2$.



If the temperature is to be constant, we have

heat gained = heat lost (1)

If there is no additional heat source, the heat absorbed from the Sun is equal to the heat radiated.

$$(\pi R^2)(\text{solar constant}) = (4\pi R^2)(\text{Stefan-Boltzmann constant})T^4 \quad (2)$$

If the distance from the Sun to the object is not 1 AU, we have to take into account the sunlight falling off with the square of the distance. If the Bond albedo is not zero, as for a blackbody, only the fraction (1 – Bond albedo) of the sunlight will be absorbed. Then

$$\frac{(\pi R^2)(\text{solar constant})(1-\text{Bond albedo})}{(\text{distance})^2} = (4\pi R^2)(\text{Stefan}-\text{Boltzmann constant})T^4 \quad (3)$$

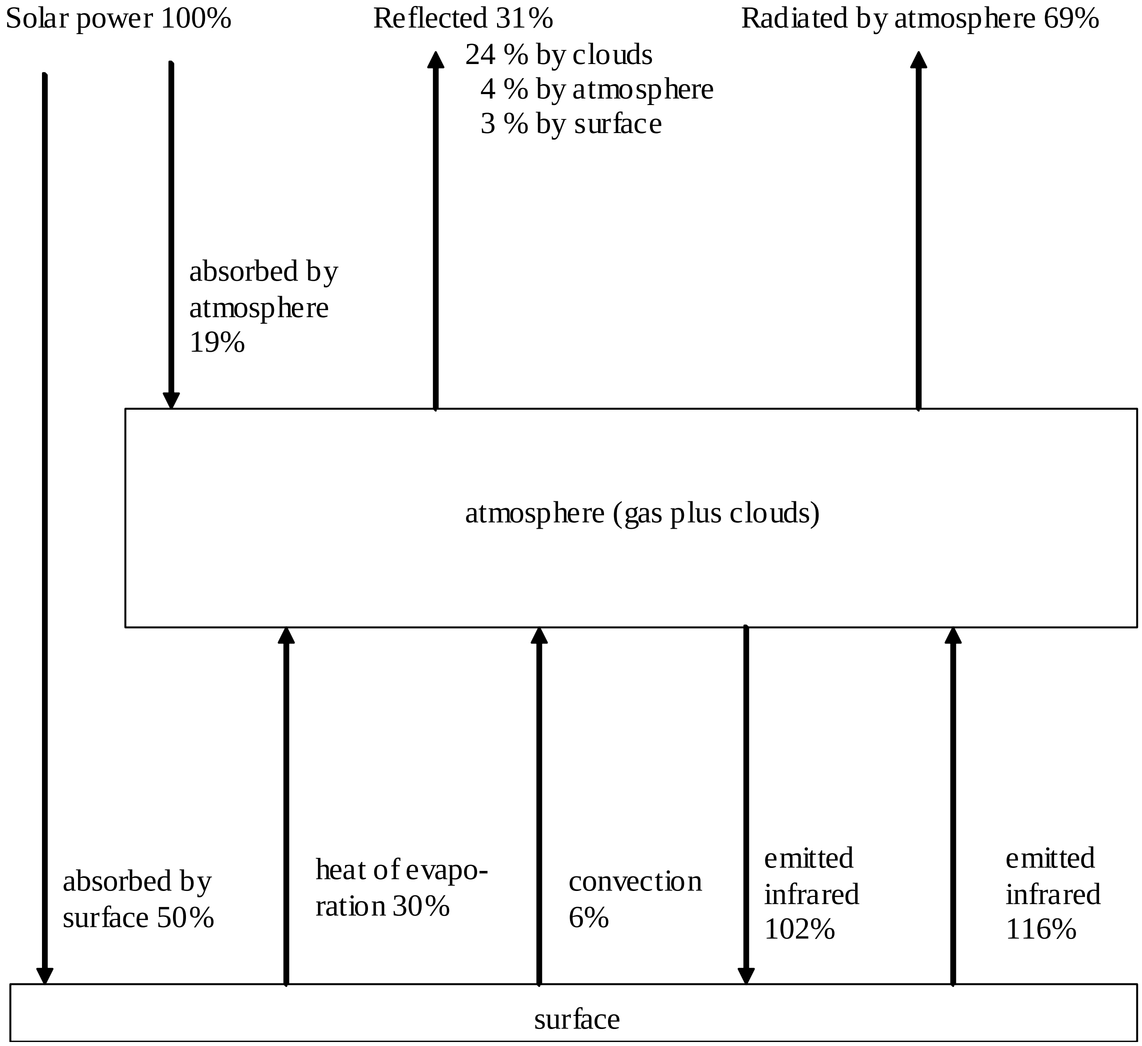
Solving this equation for the temperature T gives

$$T = \left[\frac{(\text{solar constant})(1-\text{Bond albedo})}{4(\text{Stefan-Boltzmann constant})(\text{distance})^2}\right]^{1/4} \quad (4)$$

Further complications arise when there is significant heat flow from the interior or when there is an atmosphere.

The effect of internal heat
Heat flow from the interior of an object has to be included in equation (1) if it is substantial. It can be ignored in the cases of Earth or Mars since it is swamped by the uncertainties in larger quantities. It cannot be ignored for Jupiter or its large moons. As measurements get better, heat flow from the interior will have to be included.

The effect of an atmosphere
An atmosphere acts just like a blanket that keeps you warm at night, sending most of your body heat that it absorbs back down to you. The result is a surface temperature that is higher than it would be if there were no atmosphere. Examples include Venus, Earth, Mars and Titan, a satellite of Saturn. The giant planets certainly have atmospheres, but we lack observations (except for Jupiter, a comparatively short way down).
Here is an energy balance for the Earth.



Note that the net infrared emission from the Earth is only 14% (116% - 102%). This is the greenhouse effect (the blanket).

Climate change

This is a complex subject, and the current focus is prediction by locality. 80% of recent changes to the Earth's average temperature is accounted for by only four factors:

1) The increase in carbon dioxide levels make the atmosphere more opaque in the infrared and is the largest of the effects (think of putting on a second blanket).
2) The El Niño heating of the equatorial pacific affects the Earth worldwide.
3) Violent volcanic eruptions send gases into the stratosphere. They become white powdery ammonium sulfate and reflect significant sunlight back out into space.
4) The variation in the Sun's power over the 14 year solar cycle only amounts to 0.1%, but it accounts for 2% of climate variation. The cause of this magnification is unknown.

Experiment

The first job is to type out the Excel spreadsheet shown below. Use a leading single quote for text and format the numbers as shown.

	A	B	C	D	E	F
1	Name	your name				
2	Date	the date				
3						
4	Solar constant W m^-2	1367.6				
5	Stefan-Boltzmann	5.67040E-08				
6	constant W m^-2 K^-4					
7						
8	1) the effect of distance: Mercury					
9	average Sun-Mercury distance (AU)	0.38709893				
10	eccentricity	0.20563069				
11	Bond albedo	0.068				
12	average temperature K (observed)	440				
13	distance definition	perihelion	average	aphelion		
14	Sun-Mercury distance (AU)					
15	temperature K (calculated)					
16						
17	2) the effect of albedo: satellites of Saturn					
18	average Sun-satellite distance (AU)	9.53707032				
19	satellite	Mimas	Enceladus	Tethys	Dione	Rhea
20	Bond Albedo	0.67	0.85	0.61	0.57	0.48
21	temperature K (calculated)					
22						
23	3) the effect of an internal heat source (tidal friction): satellites of Jupiter					
24	average Sun-satellite distance (AU)	5.20336301				
25	satellite	Io	Europa	Ganymede	Callisto	
26	orbit radius (km)	421800	671100	1070400	1882700	
27	Bond albedo	0.52	0.68	0.35	0.13	
28	temperature K (observed)	118	103	113	118	
29	temperature K (calculated)					
30						
31	4) the effect of atmosphere					
32	object	Venus	Earth	Mars	Titan	
33	average Sun-object distance (AU)	0.72333199	1.0000001	1.5236623	9.53707032	
34	Bond albedo	0.90	0.306	0.250	0.248	
35	surface atmospheric pressure (bar)	92	1.014	0.00636	1.6	
36	temperature K (observed)	737	288	213	94	
37	temperature K (calculated)					
38						
39	Questions					
40	1) What is the effect of distance from the Sun on the temperature of an object?					
41						
42	2) What is the effect of albedo on the temperature of an object?					
43						
44	3) For satellites of Jupiter, what is the effect of orbit radius on the degree of internal heating?					
45						
46	4) The atmospheres of Venus and Mars are mostly composed of carbon dioxide, a greenhouse gas.					
47	Why is there an extreme greenhouse effect on Venus and hardly any on Mars?					
48						
49						

Sheet1

The four parts of the experiment illustrate major effects on temperature. Cases have been selected according to the quality of the observations.

Step 1

Mercury's orbit has a large eccentricity, so there is a large change in the Sun-Mercury distance as Mercury goes around the Sun. The Sun-Mercury distance is determined from the average distance (the orbit semi-major axis, a) and the eccentricity, e. Thus:

Case	Sun-Mercury distance
perihelion	a (1-e)
average	a
aphelion	a (1+e)

The temperature of Mercury is found using equation (4) on page 2. Fill in the spread-sheet boxes as given below.

Box	Entry	Format as
B14	+B9*(1-B10)	number, 8 decimal places
C14	+B9	number, 8 decimal places
D14	+B9*(1+B10)	number, 8 decimal places
B15	+(B4*(1-B11)/(4*B5*B14^2))^(1/4)	number, 0 decimal places
C15	+(B4*(1-B11)/(4*B5*C14^2))^(1/4)	number, 0 decimal places
D15	+(B4*(1-B11)/(4*B5*D14^2))^(1/4)	number, 0 decimal places

Step 2

Large satellites of Saturn have been extensively observed by the Cassini spacecraft, and the Bond albedos have been measured. Five satellites have been selected to illustrate the effect of albedo on temperature. (Iapetus has been left out because it has one side that is very light and one side that is very dark; Titan has been left out because it has an atmosphere.) The average Sun-satellite distance is just the semi-major axis of the orbit of Saturn. Fill in the spreadsheet boxes as given below.

Box	Entry	Format as
B21	+(B4*(1-B20)/(4*B5*B18^2))^(1/4)	number, 0 decimal places
C21	+(B4*(1-C20)/(4*B5*B18^2))^(1/4)	number, 0 decimal places
D21	+(B4*(1-D20)/(4*B5*B18^2))^(1/4)	number, 0 decimal places
E21	+(B4*(1-E20)/(4*B5*B18^2))^(1/4)	number, 0 decimal places
F21	+(B4*(1-F20)/(4*B5*B18^2))^(1/4)	number, 0 decimal places

Step 3

The four large satellites of Jupiter have internal heat sources (tidal friction) that can raise the surface temperature beyond that expected from heating by the Sun. Observed temperatures are provided so that you can compare it with the calculated temperature. Orbit radii are also provided. Fill in the spreadsheet boxes as given below.

Box	Entry	Format as
B29	+(B4*(1-B27)/(4*B5*B24^2))^(1/4)	number, 0 decimal places
C29	+(B4*(1-C27)/(4*B5*B24^2))^(1/4)	number, 0 decimal places
D29	+(B4*(1-D27)/(4*B5*B24^2))^(1/4)	number, 0 decimal places
E29	+(B4*(1-E27)/(4*B5*B24^2))^(1/4)	number, 0 decimal places

Step 4

Four objects (Venus, Earth, Mars and Titan) have atmospheres and observed surface temperatures. Internal heat sources are minimal. The atmospheres have the effect of raising the surface temperature beyond that calculated from equation (4). Observed surface temperatures and gas pressures are provided. Fill in the spreadsheet boxes as given below.

Box	Entry	Format as
B37	+(B4*(1-B34)/(4*B5*B33^2))^(1/4)	number, 0 decimal places
C37	+(B4*(1-C34)/(4*B5*C33^2))^(1/4)	number, 0 decimal places
D37	+(B4*(1-D34)/(4*B5*D33^2))^(1/4)	number, 0 decimal places
E37	+(B4*(1-E34)/(4*B5*E33^2))^(1/4)	number, 0 decimal places

Questions

The questions are given on the sample spreadsheet, page 4. Answer the questions on the spreadsheet, print and hand it in.