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P5 9 The cheese-ibility of fondue on the Moon

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Abstract

This paper considers the effects of tidal heating on a moon made of cheese, with a brief discussion of solar heating, in an attempt to find the depth at which the perfect fondue can be found. The ideal temperature for fondue is 338 K and we calculated this could be found approximately 2 m away from the core.

Introduction

Cheese fondue is a Swiss dish mainly made up of melted cheese that is traditionally eaten by dipping bread and other foods in it. This paper will aim to find (assuming a perfectly spherical moon made of cheese) the depth at which the perfect fondue can be found, if at all. By finding the distribution of total thermal energy in the Moon, we can model a moon made of cheese and apply this distribution to find the 'fondue depth'.

Thermal model of the Moon

There are 3 main factors that drive the heating of the Moon; tidal forces (tidal heating), incident solar flux, and radiogenic heating. We will be ignoring radiogenic heating in this paper as when we apply this to our cheese moon, there will be no (significant) radioactive material present.

Tidal Heating

Tidal heating is a result of friction from the stretching and deformation of lunar material, the magnitude of this energy transfer depends on the dissipation of rotational and orbital energy. M. Segatz[1] states the equation for power dissipated due to tidal heating as

$$\dot{E} = -\frac{21}{2} Im(k_2) \frac{(nR_S)^5}{G} e^2 \tag{1}$$

where $\dot{E}$ is the power dissipated due to tidal heating, $Im(k_2)$ is the imaginary component of the secondary love number, n is the mean orbital motion, R_S is the radius of the satellite (for the Moon this is R_M), G is the gravitational constant and e is the eccentricity of the Moon's orbit. The secondary love number k_2 is one of three love numbers that describe how a body reacts to tidal forces. k_2 describes how the potential of a body changes when tidal forces are applied and is dependent on the rigidity, viscosity and other physical properties of the body. Calculating this number is outside the scope of this paper and is usually determined experimentally, for the Moon the generally accepted value of $Im(k_2)$ is around 0.0213 [2]. The mean orbital motion n is defined as

$$n = \frac{2\pi}{P} \tag{2}$$

where P is the orbital period of the Moon ≈ 27.3 days, therefore $n = 2.66 \times 10^{-6}$ rad s^{-1}. Substituting these values along with; $R_M = 1.74 \times 10^6$

m, $e = 0.055$ [3] and $G = 6.67 \times 10^{-11}$ m^3 kg^{-1} s^{-2} gives $\dot{E} = -21.54$ GW. So, the total thermal power dissipated in the Moon due to tidal heating is 21.54 GW. We will assume that all this heat acts on a sphere with radius 1 m at the centre of the Moon, and dissipates radially.

Solar Heating

The second form of heating we will look at in this paper is solar heating which is caused by incident solar radiation. To calculate the thermal power transferred to the lunar surface we will start with calculating the solar intensity at the Lunar surface I_M

$$I_M = \frac{L_S}{4\pi D_{S,M}^2} \tag{3}$$

Where L_S is the luminosity of the Sun (total power radiated by the sun) and $D_{S,M}$ is the distance from the Sun to the Moon. Next we must find the surface area A that this radiation will be incident on, which we will approximate as half of the surface area of the Moon at any given time.

$$A = \frac{1}{2} 4\pi R_M^2 = 2\pi R_M^2 \tag{4}$$

Using Equation (3) and Equation (4) we can calculate the power absorbed by the lunar surface P_M

$$P_M = I_M A(1 - \beta) \tag{5}$$

where β is the albedo of the Moon. Substituting $L_S = 3.83 \times 10^{26}$ W [4], $D_{S,M} \approx 1$ AU $= 1.5 \times 10^{11}$ m [5] and $\beta = 0.07$ [6] yields I$_m$ = 0.793 Wm^{-2} and $P_M = 2.40 \times 10^{16}$ W. So, the total thermal power transferred to the lunar surface is 24 PW.

The Cheese Moon

Due to surprisingly limited analysis of the thermal properties of cheeses such as Gruyère and Emmental, which are commonly used in fondue, we will have to consider a cheddar cheese moon. The ideal temperature for fondue is approximately 338.15 K, to find the distance that this temperature is achieved we must look at heat transfer at the core.

First, consider the heat transfer from a sphere of radius 1 m at the centre of the Moon. The standard expression for steady-state radial conduction heat rate through a spherical shell can be expressed as [7]

$$\dot{E} = \frac{4\pi\kappa(T_1 - T_2)}{(\frac{1}{r_1} - \frac{1}{r_2})} \tag{6}$$

where κ (0.480 W m^{-1} K^{-1} [8]) is the thermal conductivity of cheese, r_1 is the radius of the inner sphere (1 m), r_2 is the distance from the core at which fondue can be found, T_1 is the temperature of the inner sphere and T_2 is the ideal fondue temperature. T_1 can be calculated using

$$\Delta T = \frac{\dot{E}}{mC} \tag{7}$$

where m is the mass of the sphere of cheese being heated and C is the specific heat capacity of cheddar cheese. $C = 3000$ J kg^{-1} K^{-1} [8], m can be calculated using the average density of cheddar cheese and the volume of the sphere to get $m = 4482$ kg. Using these values and Equation (7), we found that $\Delta T = 1600$ K. Given that the temperature of ambient empty space is about 3 K, we know $T_1 = 1603$ K. Rearranging Equation (6) allows us to calculate r_1. The distance from the centre of the Moon where the perfect fondue can be found is at $r_1 = 2$ m from the centre.

Conclusion

After considering the magnitude and effects of tidal heating on a moon made of cheddar cheese, we have found that the perfect fondue can be found approximately 2 m from the centre. This distance is much closer to the core than we expected and is likely due to the vast disparity in thermal properties between cheese and lunar material, as well as possible oversimplification of the thermal model. The material properties of cheddar cheese indicate that a cheese moon would very likely break part almost instantly and would not sustain a stable orbit.

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