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A2 1 Boiling Water with Stars

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Abstract

In this paper we explore how long it takes to boil 1 kg of water using only the Sun, and then replace the Sun with different types of stars to compare the temperature environments on planetary surfaces. We find that the boiling time varies from a few milliseconds for the hottest stars to two and a half days for the coolest stars.

Introduction

One of the most important physical cycles on the Earth is the water cycle, which replenishes and recycles water into existing ecosystems via a constant process of evaporation and precipitation. This whole process is powered by the Sun, whose stellar properties have a significant impact on the environment here on Earth. Similarly, on exoplanets, with stars of different temperatures, any water present will be driven through a similar cycle at a differing rate, which could affect the chemical processes occurring there significantly. In this paper we will explore what happens to the speed of the evaporation of water when the Sun is replaced by other stars of different stellar types.

Theory

To gain our insight into the effect replacing the Sun with other stellar types will have, we propose a simple thought experiment. One litre of water is left fully exposed to sunlight in a 1m by 1m container. We assume that no energy is lost to the surroundings. We also assume the atmosphere is completely optically transparent, and that air pressure is comparable to that at sea level. We then calculate how much energy it would take to heat the water from room temperature (20°C) to boiling, and then how much energy it would take to totally vapourise the water. Finally, we calculate the solar power flux incident on the water's surface, and find the time it takes for this power to provide the energy necessary to boil this water.

Equations

The energy required to totally evaporate 1 kg of water is given by

$$E_{total} = Cm\Delta T + 2.26 \times 10^6 \qquad (1)$$

where C= 4186 J/kg°C is the specific heat capacity of water [1] and 2.26×10^6 J/kg is the latent heat of vapourisation for 1 kg of water [2]. The mass $m = 1$ kg and the temperature change $\Delta T = 100°\text{C} - 20°\text{C} = 80°\text{C}$. This energy totals to about 2.6×10^6 J.

The power output of a star of temperature T per square metre is given by σT^4 where $\sigma = 5.67 \times 10^{-8}$ W m^{-2} K^{-4} is the Stefan-Boltzmann constant. We then sum this over the surface area of the star, given by $4\pi r^2$ where r is the radius of the star, giving us a power output that we

Stellar Type	M	K	G	F	A	B	O
Temperature (K)	3200	4500	5800	6500	8500	20000	40000
Solar Power (W m^{-2})	11.6	324	1370	3725	18600	4,900,000	316,000,000
Time (seconds)	223000	8000	1900	700	140	0.53	0.008

Table 1: The typical temperature, power flux and boiling time for each stellar type

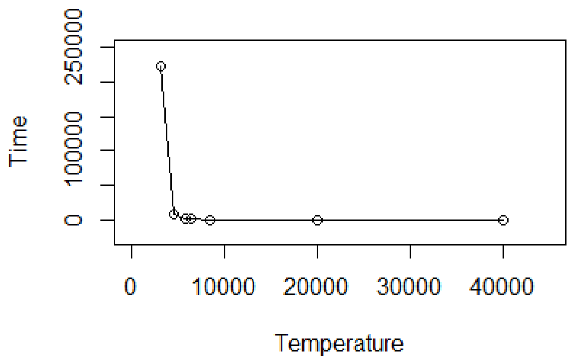

Figure 1: A graph of stellar temperature against the time taken to completely evaporate the water. Note how most values are condensed in a similar region, with the outer points reaching into extreme values

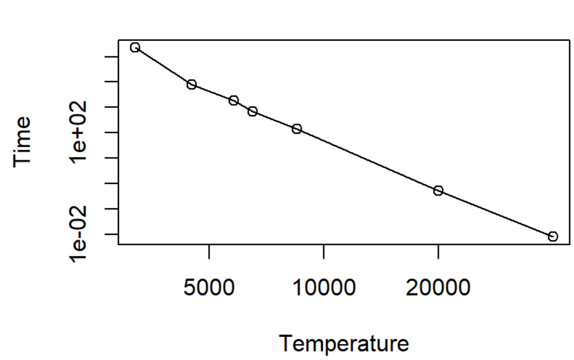

Figure 2: Temperature against time on a logarithmic scale

must then divide across the surface of a sphere of radius equal to the Earth's distance to the Sun d, which has a surface area $4\pi d^2$, to get the power incident on Earth per square metre. When we put all this into one equation and simplify we get

$$S = \sigma T^4 r^2 / d^2, \tag{2}$$

For our purposes, we will assume d is constant at 1 A.U. (1.5×10^{11} m). For typical G type stars like our Sun, the black-body temperature is about 5800 K [3], which gives an S value of about 1370 W m^{-2}. Dividing this by our energy requirement gives us

$$2.6 \times 10^6 / 1370 = 1894 \tag{3}$$

which is about 32 minutes. Applying this to the average power output of other common stellar types [3] we can generate Table 1.

Conclusion

The difference between the extreme star types is immense, with average temperatures of the hottest and coolest stars differing by ~37,000 K. The hottest stars can boil the litre of water in a couple of milliseconds, while the coolest stars take days. We can see that the power output of a star quickly reaches very high values at high temperatures, while at the lowest temperatures it is likely that, at this distance, the heat would be dissipated far before it can boil the water.

References

[1] Open University (2008). S104 Book 3 Energy and Light, p. 179.

[2] `https://www.engineeringtoolbox.com/fluids-evaporation-latent-heat-d_147.html` [Accessed 3 October 2023]

[3] `https://astrobackyard.com/types-of-stars/` [Accessed 3 October 2023]