Yarkovsky effect and interpreting it as a heat engine

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[Ralph D. Lorenz and Joseph N. Spitale, 2004, The Yarkovsky effect as a heat engine, Icarus 170, 229-233]

What is Yarkovsky effect?

- Radiation force acting on a rotating body caused by anisotropic radiation of heat of the body

- Diurnal Yarkovsky effect

  - due to temperature difference by roration

- Seasonal Yarkovsky effect

  - due to temperature distribution by eccentricity of orbit

- The effect was discovered by the Russian engineer Ivan Osipovich Yarkovsky (1844–1902)
- The effect has been directly observed by orbit of Asteroid 6489 Golevka (Chesley et al., 2003)

Why Yarkovsky effect is important?

- It can significantly modify the orbits of bodies in 1m to 10 km range.

- Recently, the significant uncertainty in orbit of small bodies from uncertainty in Yarkovsky effect.

-> The precise calculation of Yarkovsky effect is important.

Yarkovsky effect calculation

- Usual method for calculation of Yarkovsky effect is computation from dynamical view.

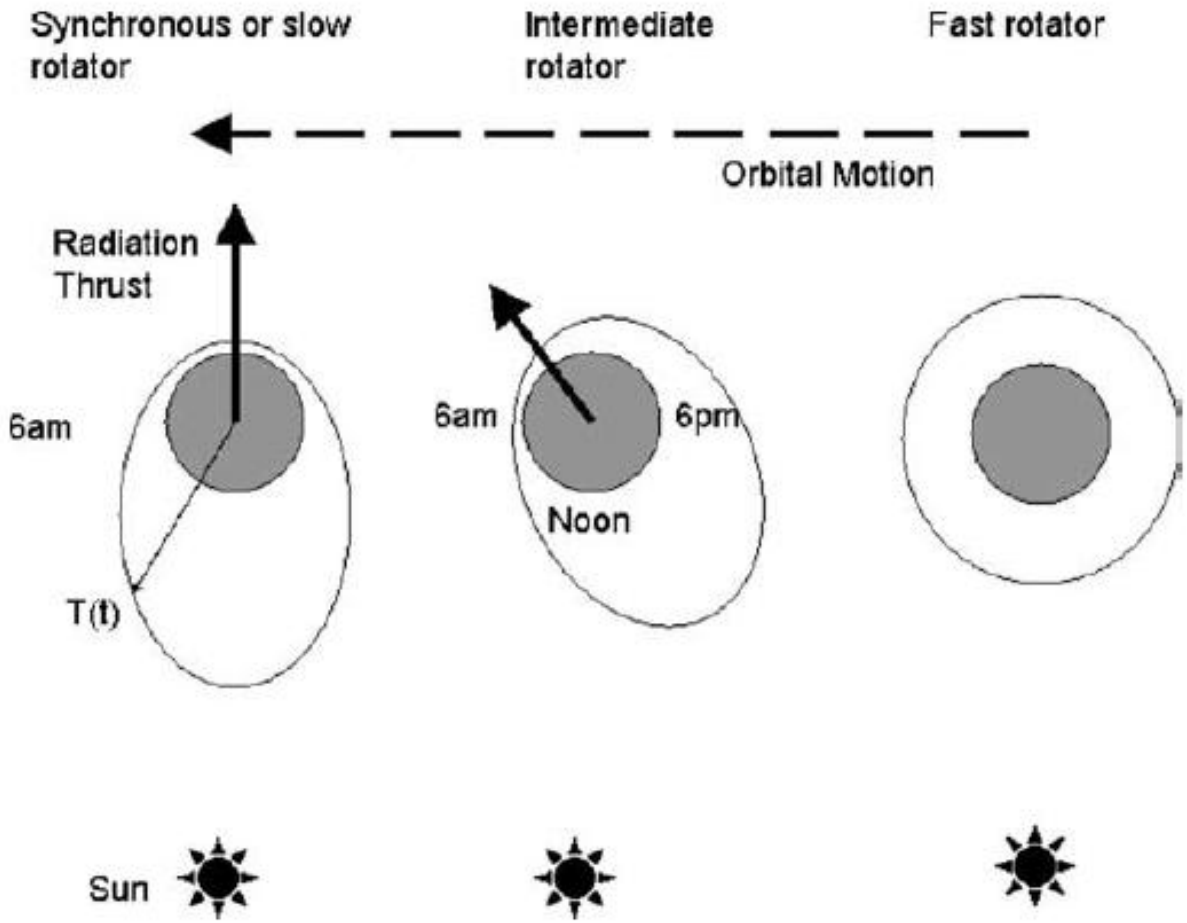
  : calculating temperature distribution of body analytically or numerically, then calculating radiative forces on each element surface of the body.

  -> shortcoming : need explicit momentum and direction of photon

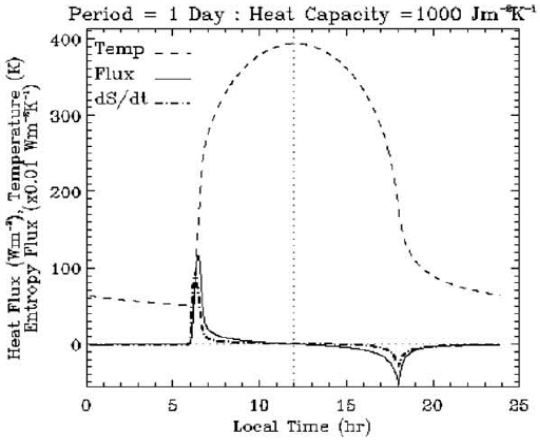
- Try calculation from thermodynamical view.

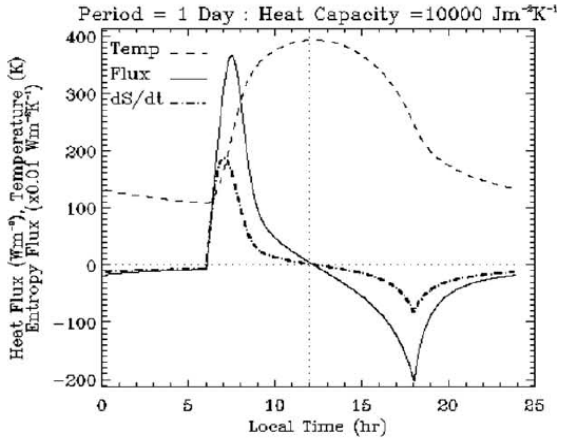
- Since work on body is done by heat, thermodynamic laws must apply to body.

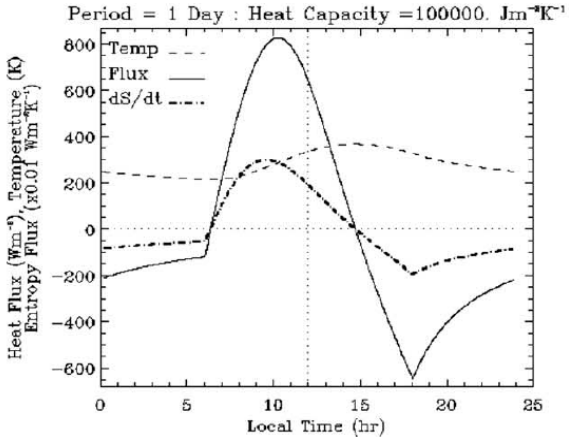
Schematic of the Yarkovsky effect

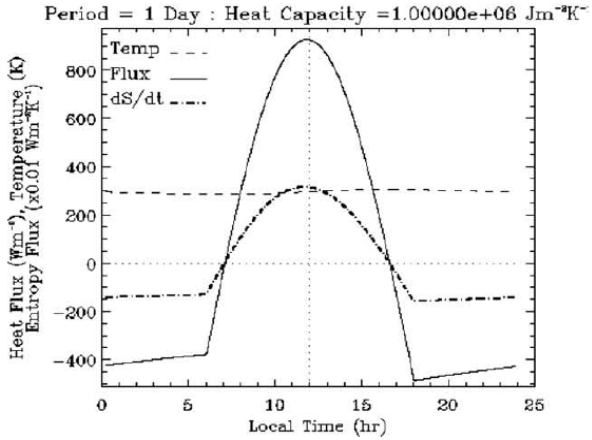


Temperature and Heat flux for various heat capacity





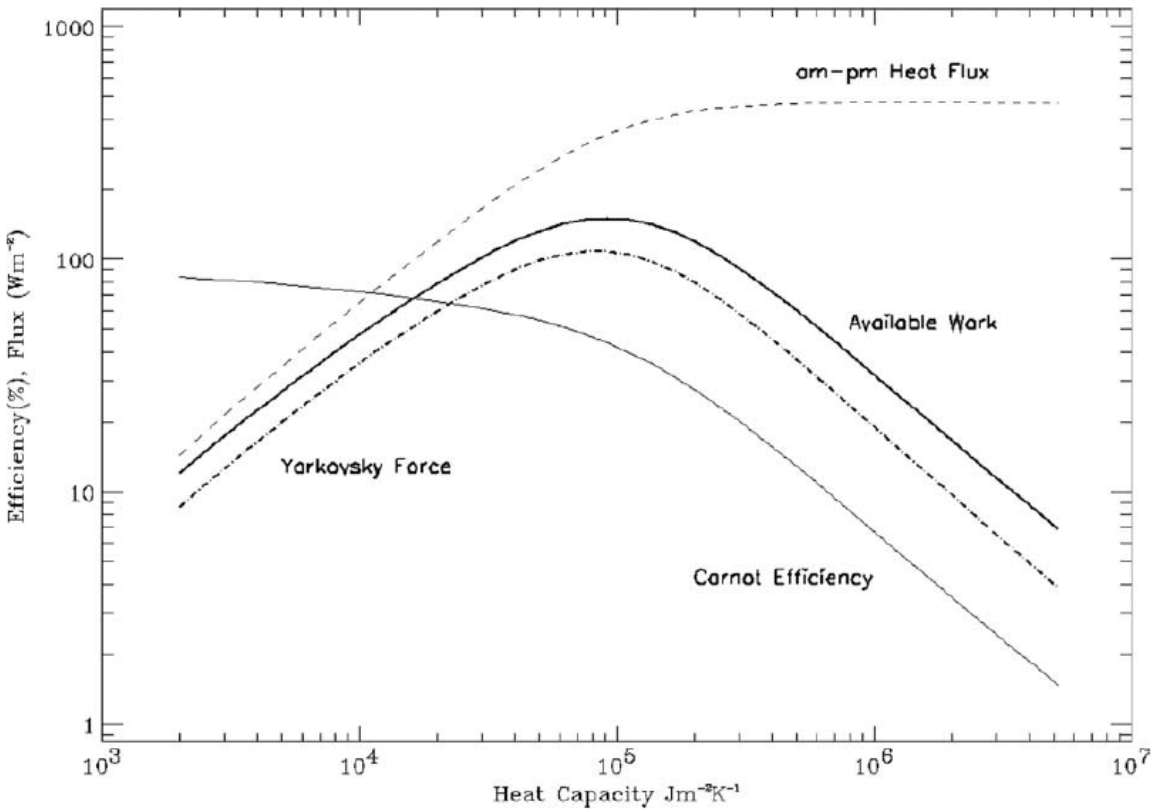




- Assumptions :
  - Cylindrical body
  - Black body
  - ignore conduction
  - using incoming flux as solar flux at 1AU
- Integrated area btw 0~12 hours represents effective am-pm heat flux

$$C\frac{dT}{dt} = P_{in} - P_{out} = \begin{cases} F\,\mathrm{Cos}(\omega t + \pi) - \sigma T^4 & \text{when } 6 < t\ (\text{hour}) < 18\ (\textit{day time}) \\ -\sigma T^4 & \text{when } 0 < t < 6,\ \ 18 < t < 24\ (\textit{night time}) \end{cases}$$

The am-pm heat flux, Carnot efficiency, Available work, and resulting Yarkovsky force in the direction of motion for various heat capacity



- The am-pm heat flux tend to increases as heat capacity increases
- Carnot efficiency :
  - Corresponding to $\Delta T/T$
  - Maximum heat-to-work conversion efficiency
  - Decreases as heat capacity increases
- Available work is product of above two.
- Propulsive efficiency

Summary

- Yarkovsky effect is important to expect orbit of small bodies (1m-1km range).

- Yarkovsky could be calculated from thermodynamics view, and result is consistent with the result using from usual dynamic method

- Yarkovsky effect has maximum value at intermediate heat capacity. It is consistent with the expectation.

Appendix

- A simple linearized expression for Yarkovsky effect is

$$F_y = \frac{8}{3}\pi R^2 \frac{\sigma T^4}{c}\frac{\Delta T}{T}$$