Gas production of 67P/CG: the limitations of static two layer models.

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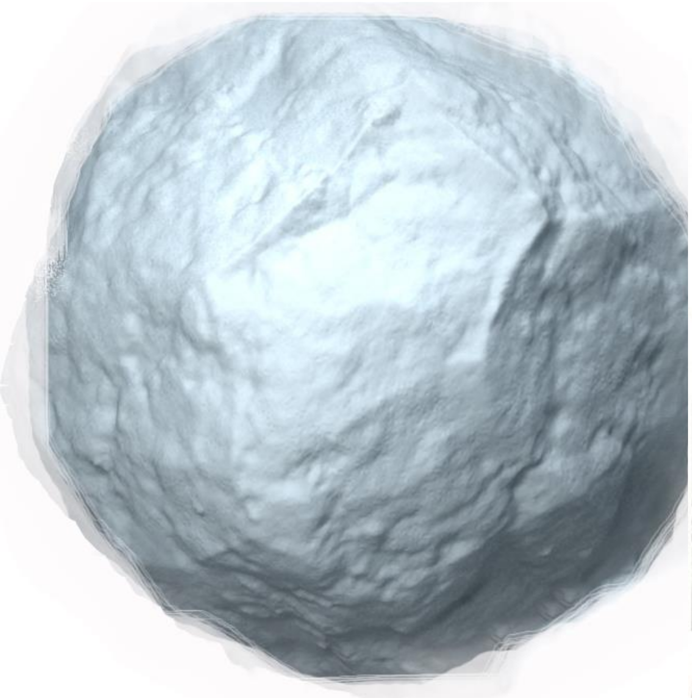
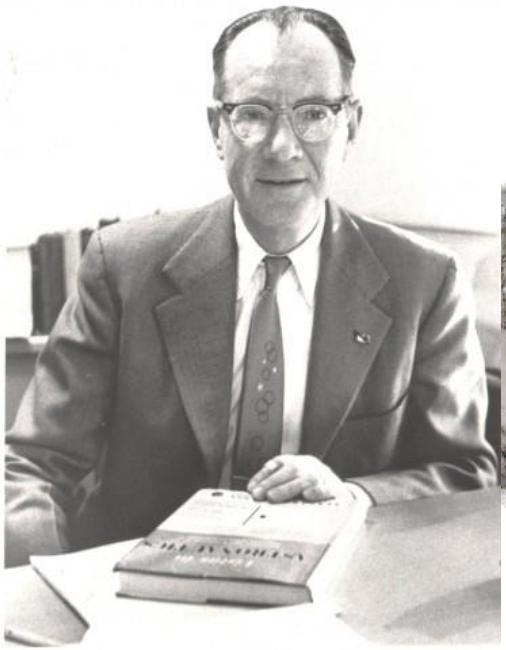
“Gold ages”: Whipple's Comet Model. Snowball and Dirty Snowball

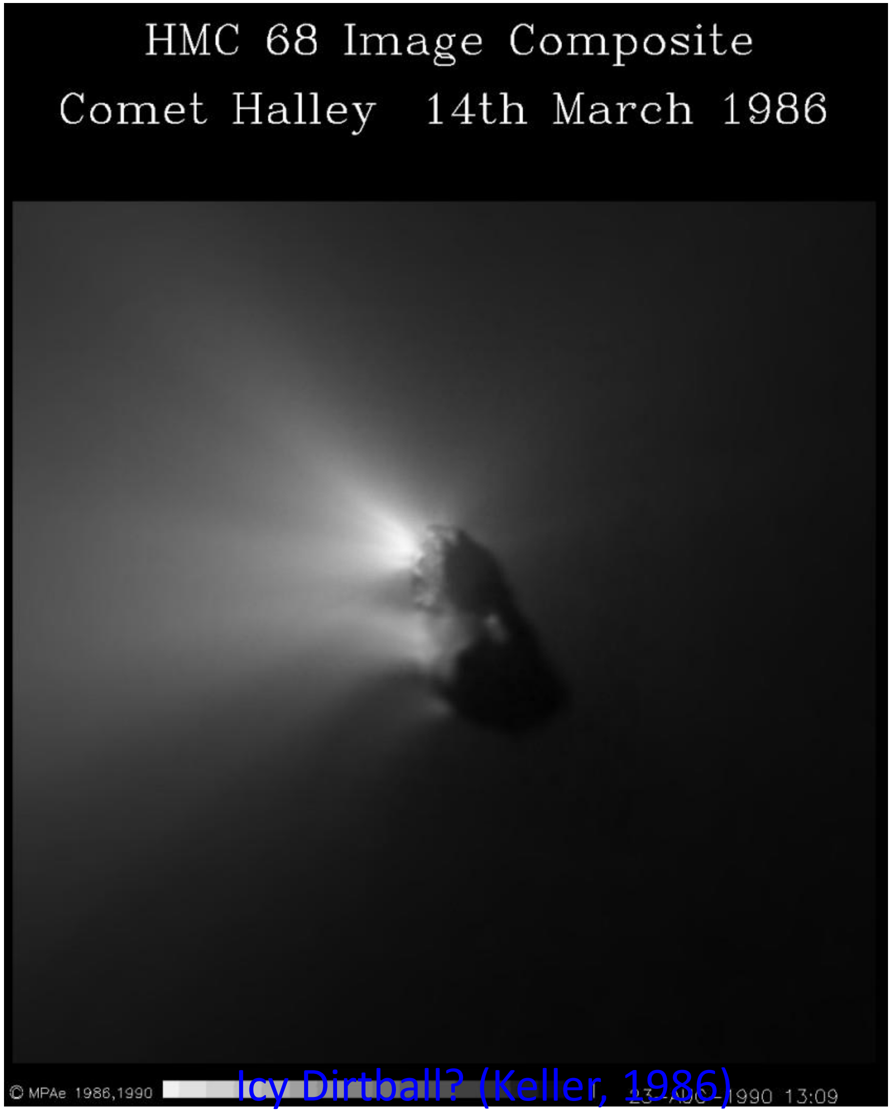




Idea: icy conglomerate (later dirty snowball) –
sublimation – reactive force –
non-gravitational corrections

Model: Solar radiation – Absorption – Sublimation
<u>One algebraic equation of energy balance</u>!

Comet Halley: Giotto and Vegas



Icy Dirtball? (Keller, 1986)

- Confirmation of Whipple's idea
- Questions for the new theory

Nucleus:

- slightly red and dark with an albedo of 0.04

- surface temperature to be in the range 300–400 K

- heterogeneous

- dust to gas ratios of about 2

- best estimate for the density is around 0.6 g cm-3

- the observed topography indicates structural strength of the surface.

NEW MODELS ARE NEEDED

Development of models. XX

Fanale and Salvail, An idealized short-period comet model, Icarus, 1984.

Gombosi et al. 1986-
Prialnik et al. 1987-
Koemle et al. 1989-
Kührt et al. 1991-
de Sanctis et al. 1996-
Enzian et al. 1996-

New players:
Dust
Porosity
Conductivity

Heat diffusion equation

$$\rho c(T)\frac{\partial T}{\partial t} = \nabla(k(T,\mathbf{r})\nabla T)$$

$$E_{Abs}(t) = \varepsilon\sigma T^4 - k(T)\nabla T$$

$$E_{Sub}(t) = k(T)\nabla T$$

Here T is temperature, t is time, $\rho(x,t)$ is density, $c(T,x,t)$ is heat capacity, $k(T,x,t)$ is conductivity

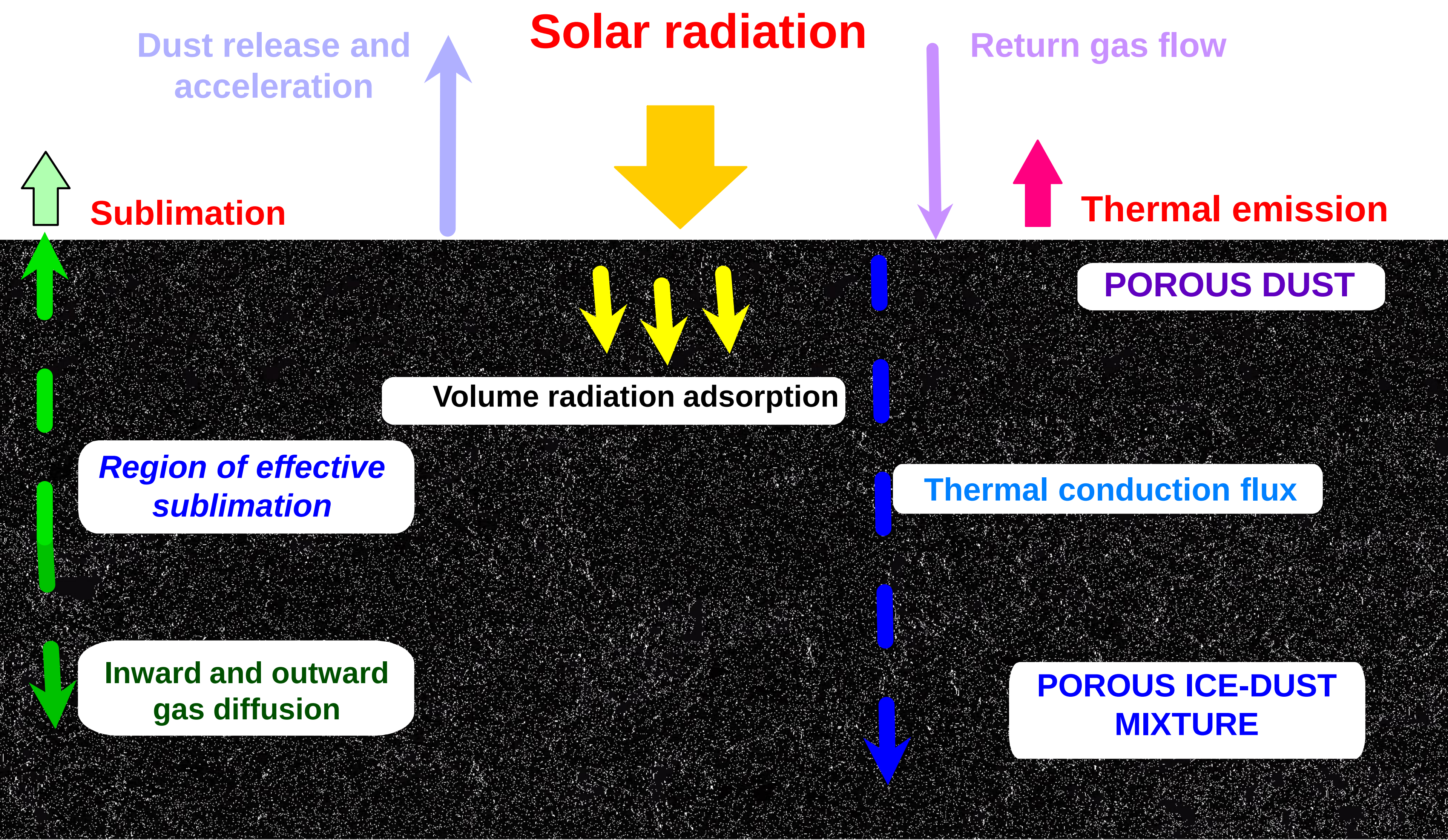
Gas diffusion equation

$$\psi\frac{\partial \rho_g}{\partial t} = -\frac{\partial \phi_g}{\partial x} + q\,,\quad \phi_g = -\frac{8\psi r_c}{3}\frac{\partial I_s}{\partial x}\,,$$

$$q = -\frac{8\psi r_c}{3}\frac{\partial}{\partial x}\left[I_s(T)\frac{b}{T^2}\frac{\partial T}{\partial x}\right].$$

Here ψ is porosity, ρ_g is density of the vapor, φ_g is the vertical gas flux through a tube with icy walls, q is the local gas production in the interior, I_s is the sublimation rate of an icy surface

Draft of near-surface layer



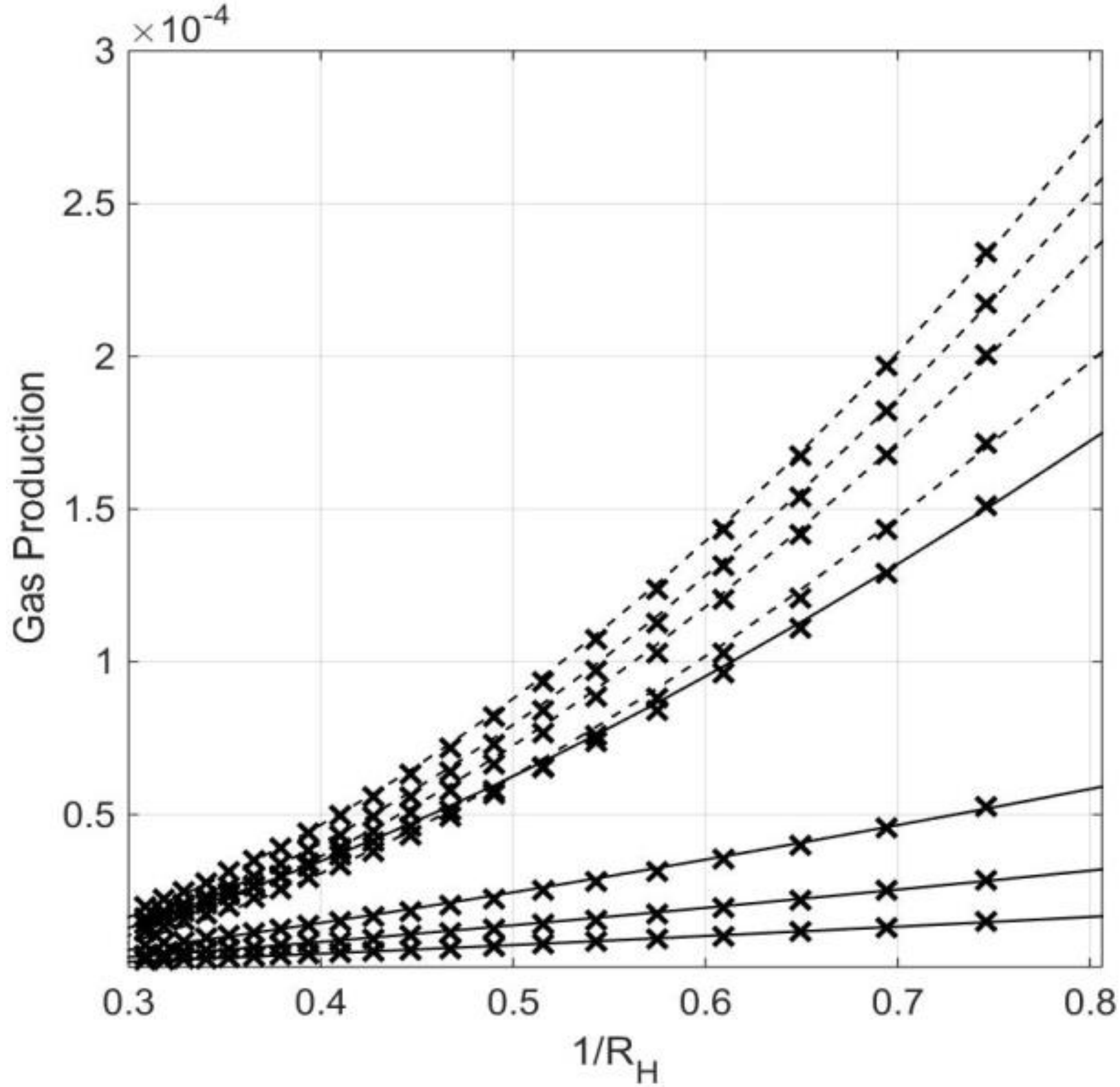
Insertion of fixed dust layer

$$I_s x^2 = A_{tr} T_d^4 + A_c (T_d - T_i),$$
$$A_c (T_d - T_i) = E_G(x).$$

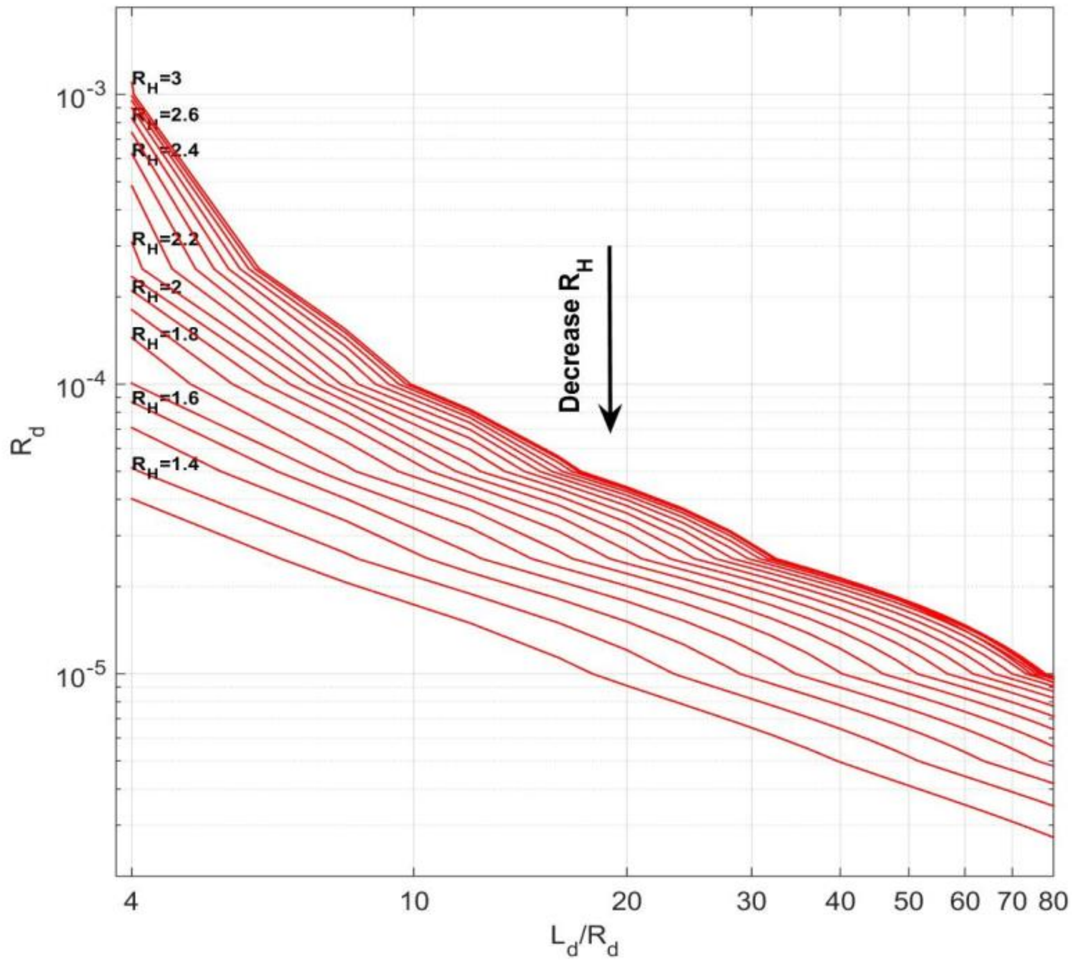
$$E_G(x) = \Psi(R_d, L_d) E_{sub} G(x),$$
$$G_\epsilon(x) = a_g x^{2+\epsilon},$$

Insertion of radiative conduction and core heating

$$I_s x^2 = A_{th} T_d^4 + (\lambda + \lambda_{th} T_d^3)/L_d (T_d - T_i)$$
$$(\lambda + \lambda_{th} T_d^3)/L_d (T_d - T_i) = E_G(x) + \lambda (T_i - T_{core})/L_{core}$$

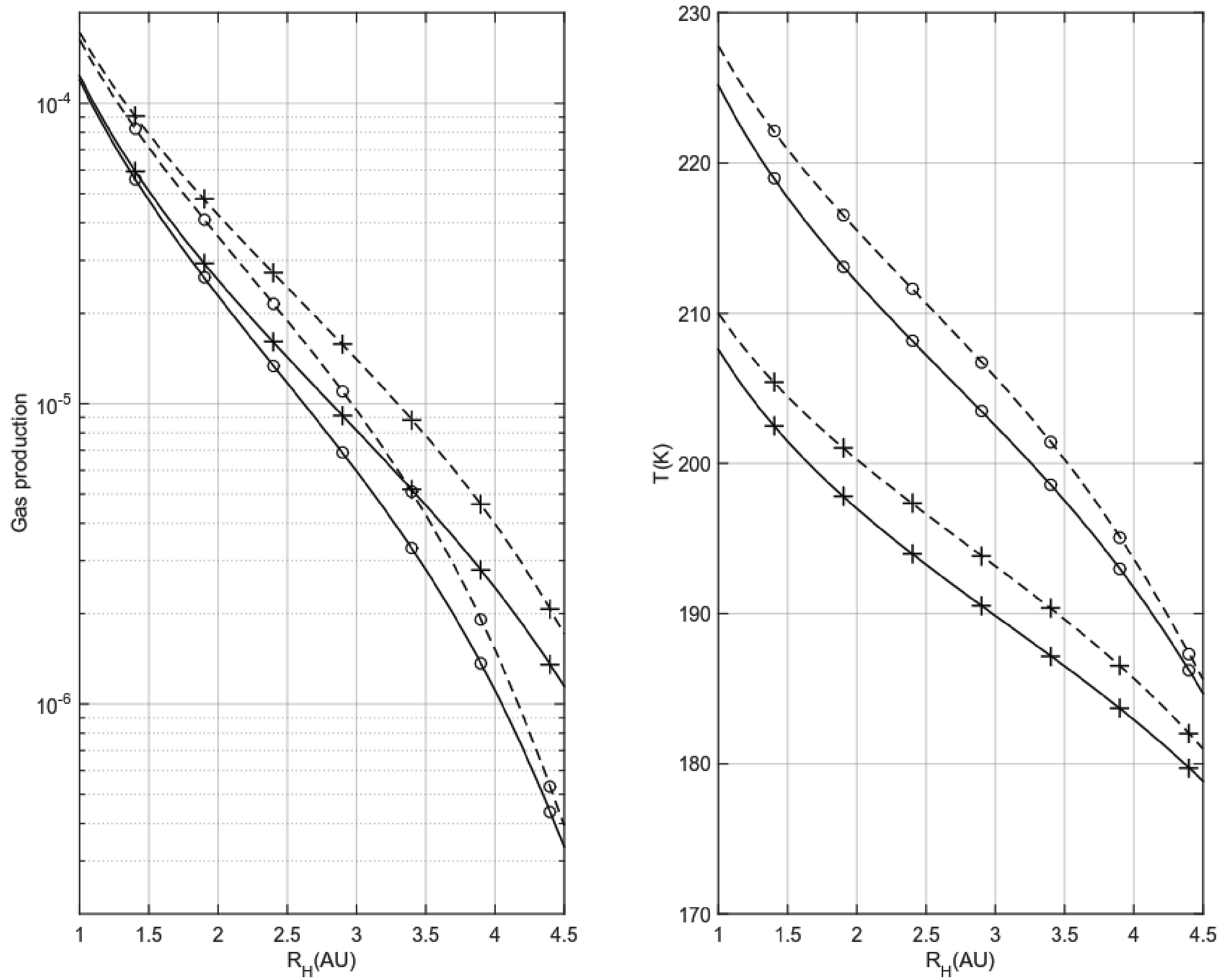


Gas production (in kg/(m2 s)) as a function of 1/R_H (R_H in AU). Grain size is 5µm (dashed curves) and 100 µm (solid curves). Layer dimensionless thickness Ld /Rd is 4,20,40,80. Crosses show a quadratic approximation.

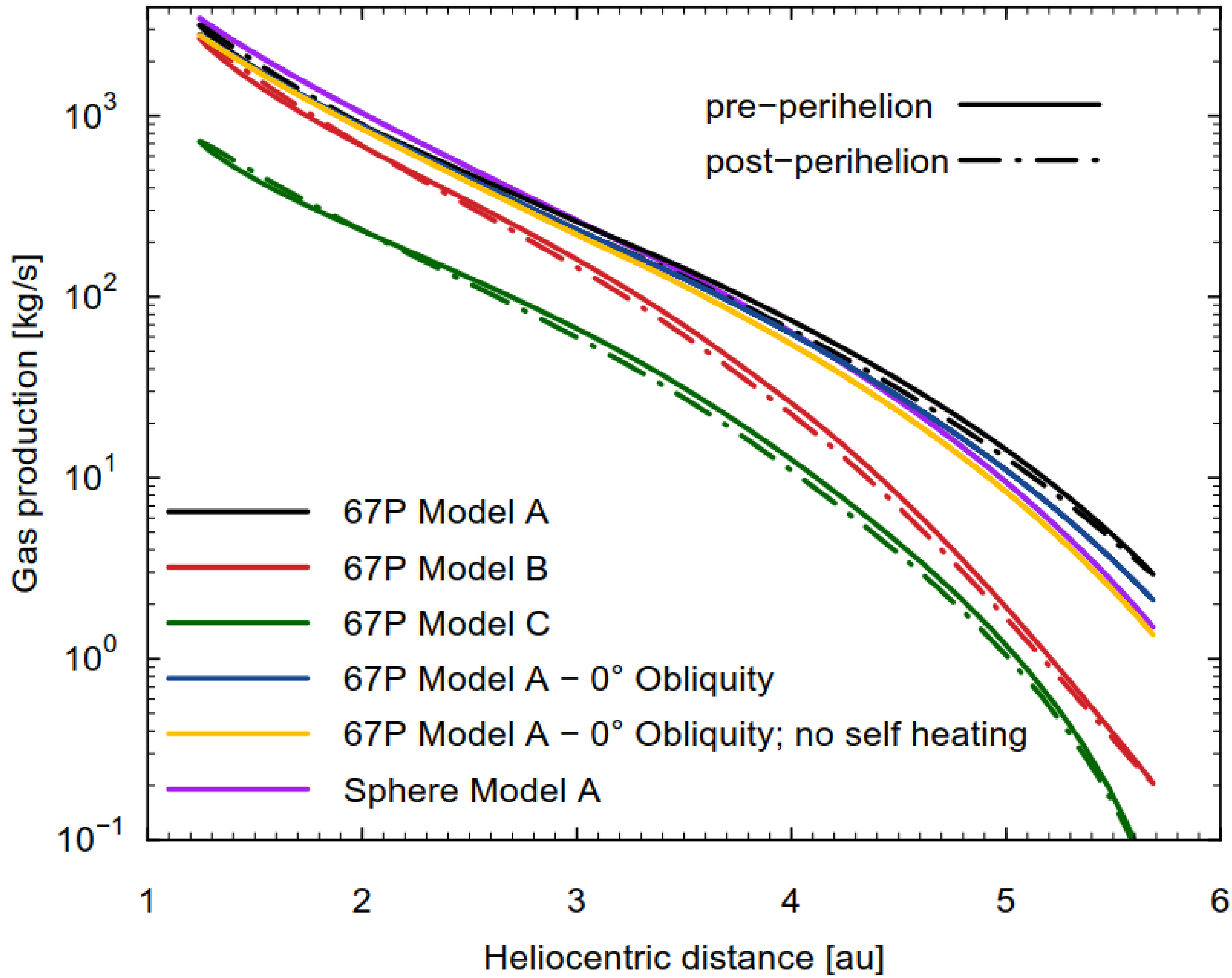


One can predict how the characteristics of the layer should change, in order to satisfy the given dependence of the production rate on heliocentric distance. Suppose that the observed production changes as $R\_H^{-3.5}$ and the grain size *R_d* is fixed. Under such assumptions we can evaluate the required changes of the layer thickness *L_d* . Results of simulations are shown in figure: each curve shows pairs of values (*L_d* and *R_d*) for different distances *R_H* . Now, for the fixed R^d passing from one curve to another (decreasing the distance *R_H*), **we see how the thickness of the layer should change. For example, for R_d = 10μm the dimensionless layer thickness should decrease from about 80 at R_H =2AU to about 20 at perihelion of 67P. Note that in our idealized test case the particle size can not be greater than 50 − 60μm.**

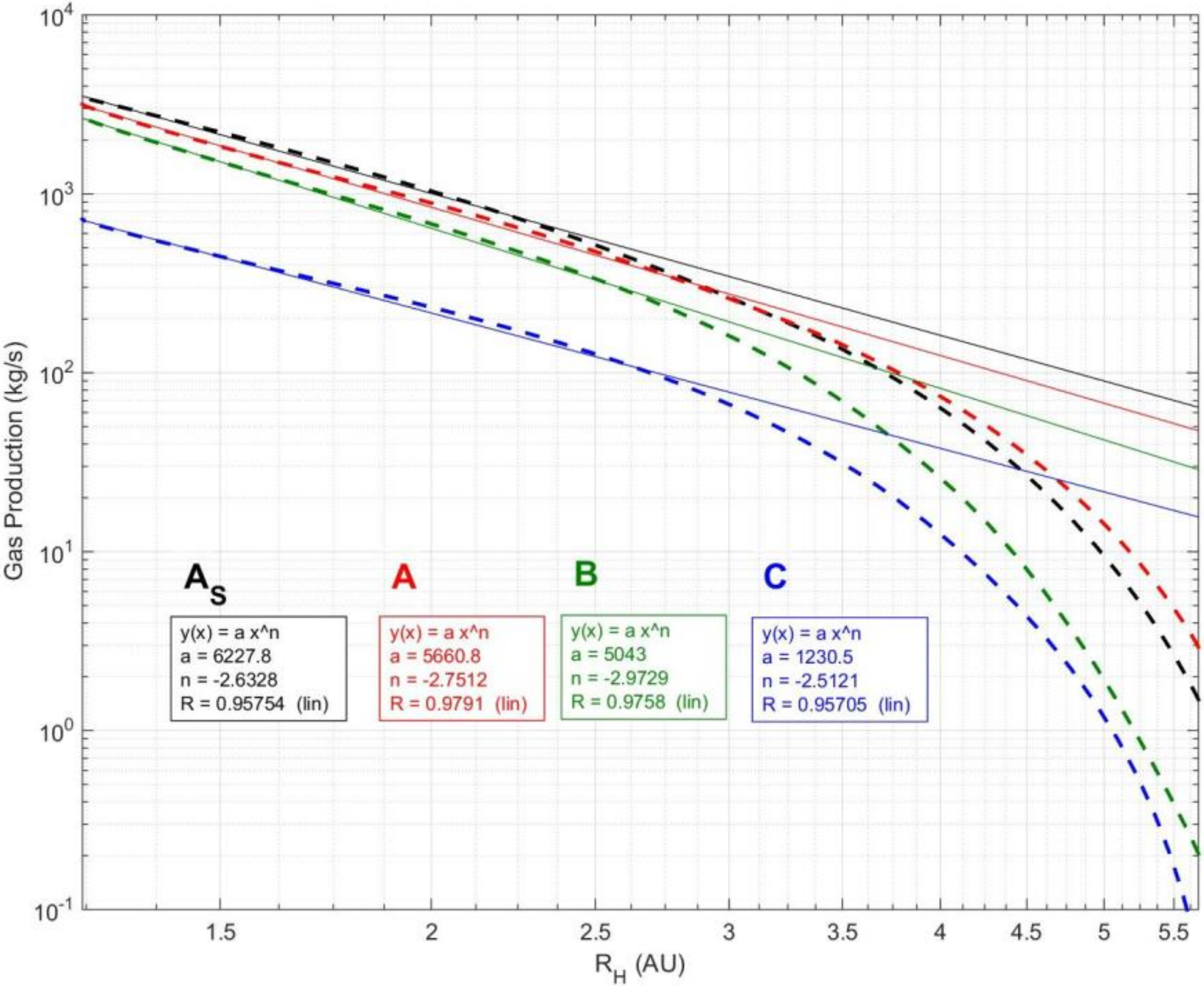
Insertion "icy area fraction"



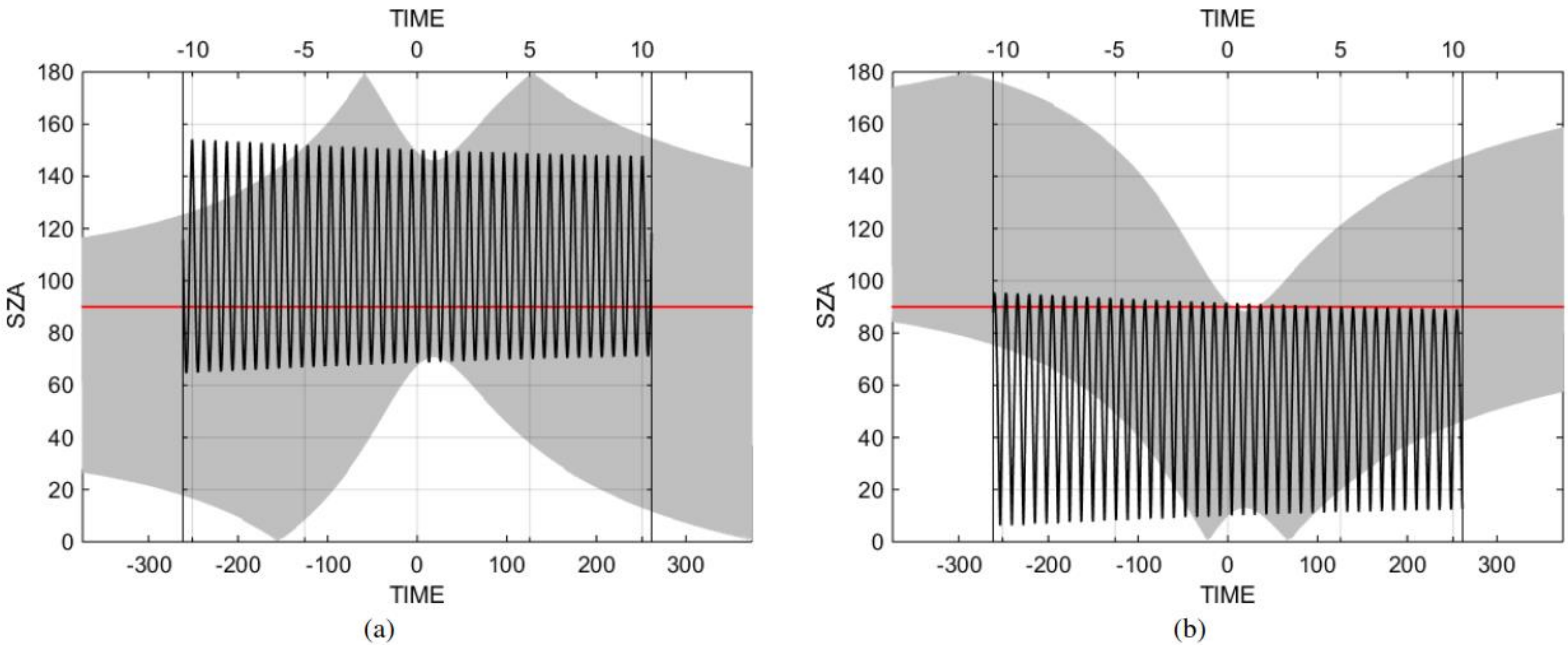
Gas production (left panel) and ice temperature at the bottom of the overlying porous dust layer (right panel) as a function of the heliocentric distance R_H calculated at the equator of a rotating spherical nucleus with zero-obliquity. Grain size is 100µm (dashed curves) and 1 mm (solid curves). “Icy surface area” factor fi equals 0.1 (marked with open circles) and 1 (marked with crosses).



Total gas production as a function of the heliocentric distance RH . Simulation results are shown for: CG SHAP7 models A, B, C; CG SHAP7 model A for a zero-obliquity with and without self heating (SH); sphere model A. Indeed the slope of the production without self heating is higher than the one with self heating, but still not quite as high as the one for the sphere.



Gas Production (kg/s)
R_H (AU)
A_S
A
B
C
y(x) = a x^n
a = 6227.8
n = -2.6328
R = 0.95754 (lin)
y(x) = a x^n
a = 5660.8
n = -2.7512
R = 0.9791 (lin)
y(x) = a x^n
a = 5043
n = -2.9729
R = 0.9758 (lin)
y(x) = a x^n
a = 1230.5
n = -2.5121
R = 0.95705 (lin)



Solar zenith angle as a function of time for points 1 (Seth) and 2 (Hatmehit). On X-axis: SZA in degrees, on Y-axis: days from perihelion. The exact location are indicated on the shape model in Fig. A.1.

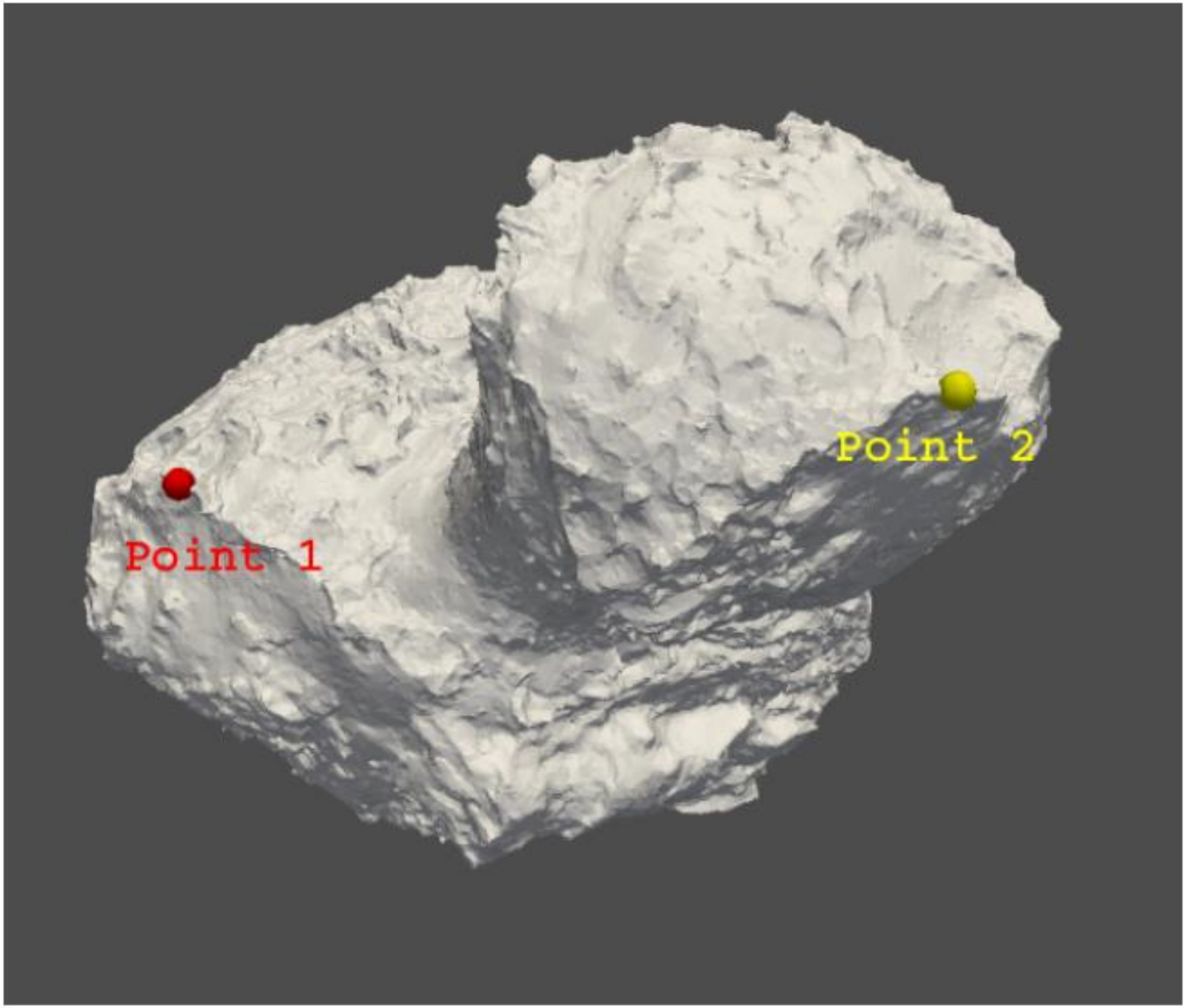
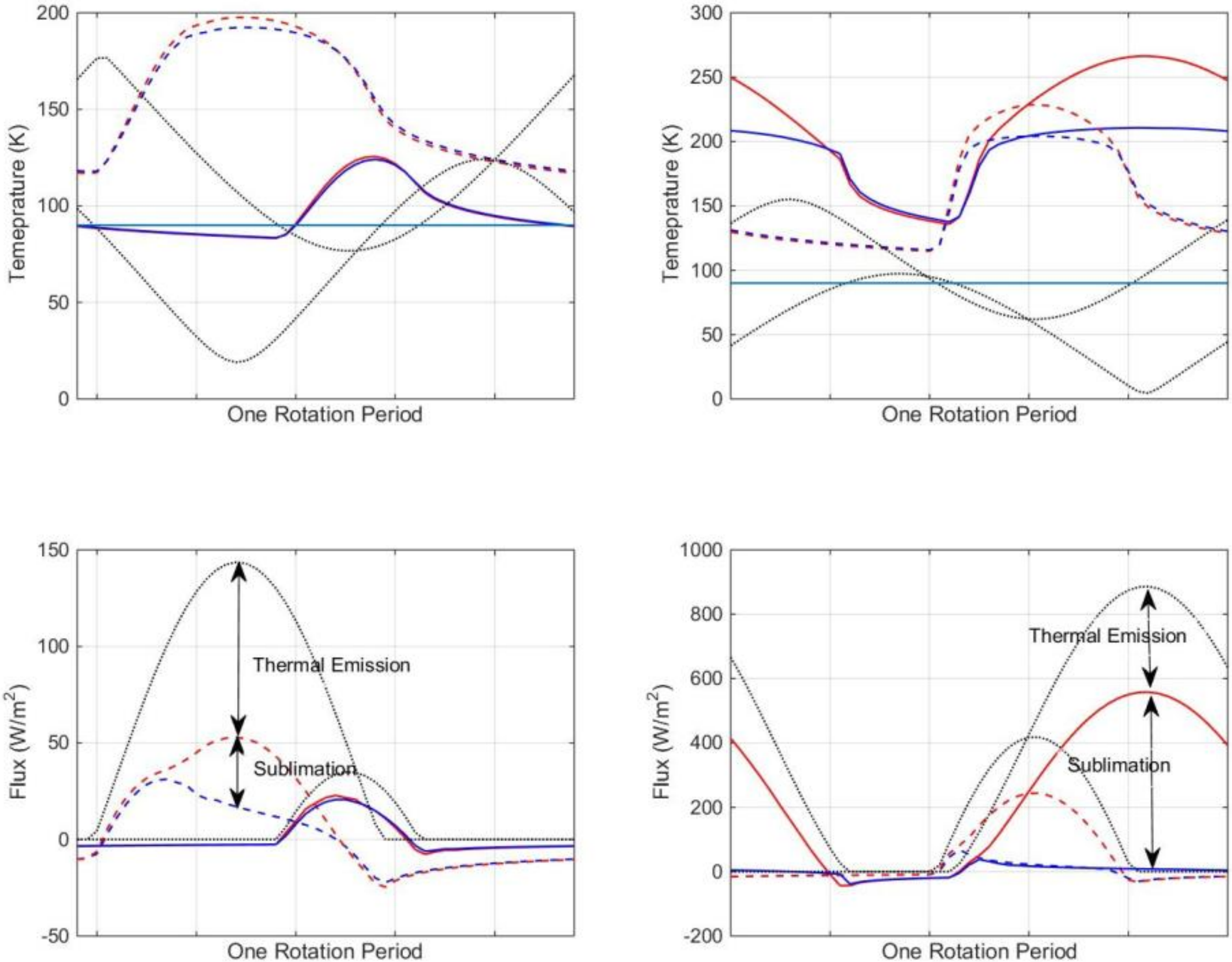


Fig. A.1: The two points used for the non-linear, non-stationary thermal modeling discussed in the context of Figure 8 and 9. Red and yellow points show the location for the point 1 (Seth) and 2 (Hatmehit) region respectively.



Temperatures (top row) and energy fluxes (bottom row) as a function of time for points 1 and 2. The results are presented for distances of 3 AU and 1.24 AU in the left column and in the right column, respectively.

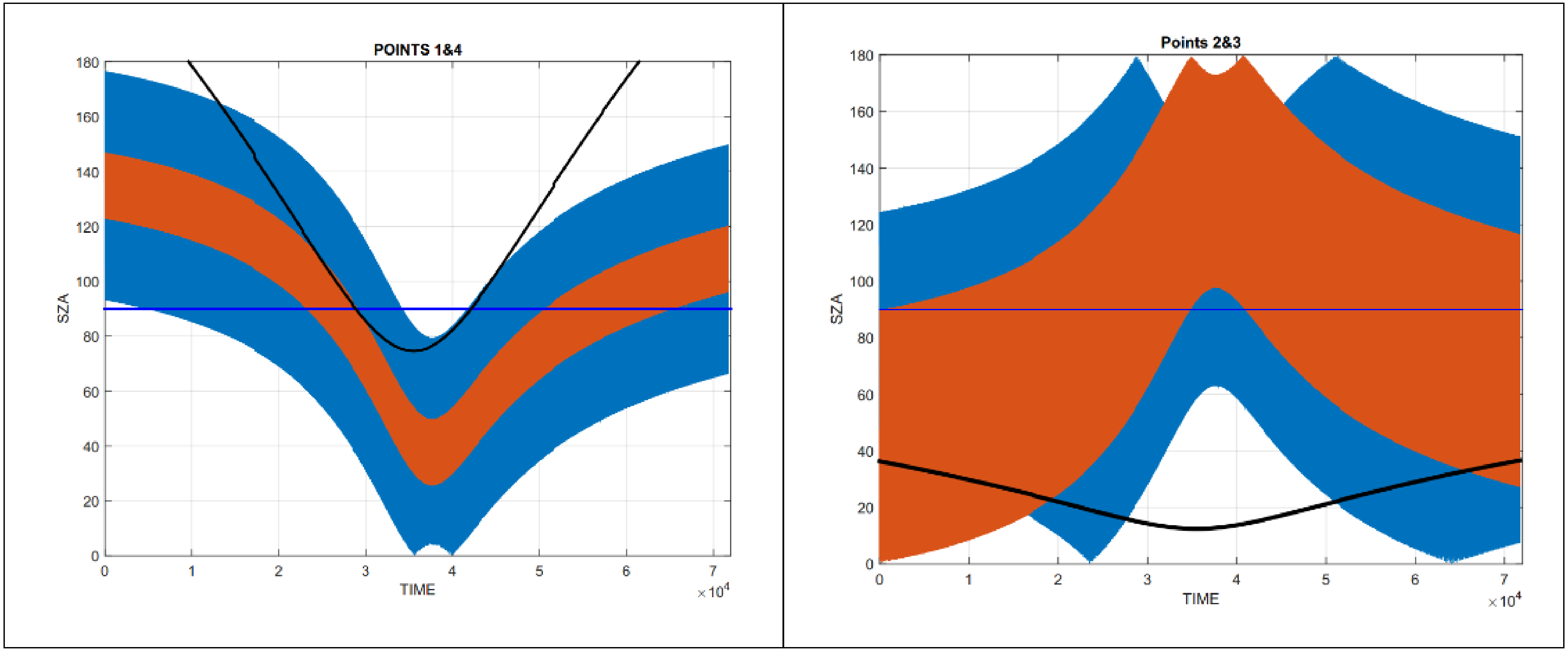


Fig. 1. SZA in degrees as a function of time for 4 points from Fig. 2. Black curve shows the heliocentric distance in arbitrary units. The daily variations merge, there are more than 70,000 points on each curve. But one can clearly see the amplitude of the daily variation and the orbital motion. Thus, near perihelion there is ~"polar day" for points 1 and 4, there is ~"polar night" for point 3, and "normal diurnal variations" for point 2.

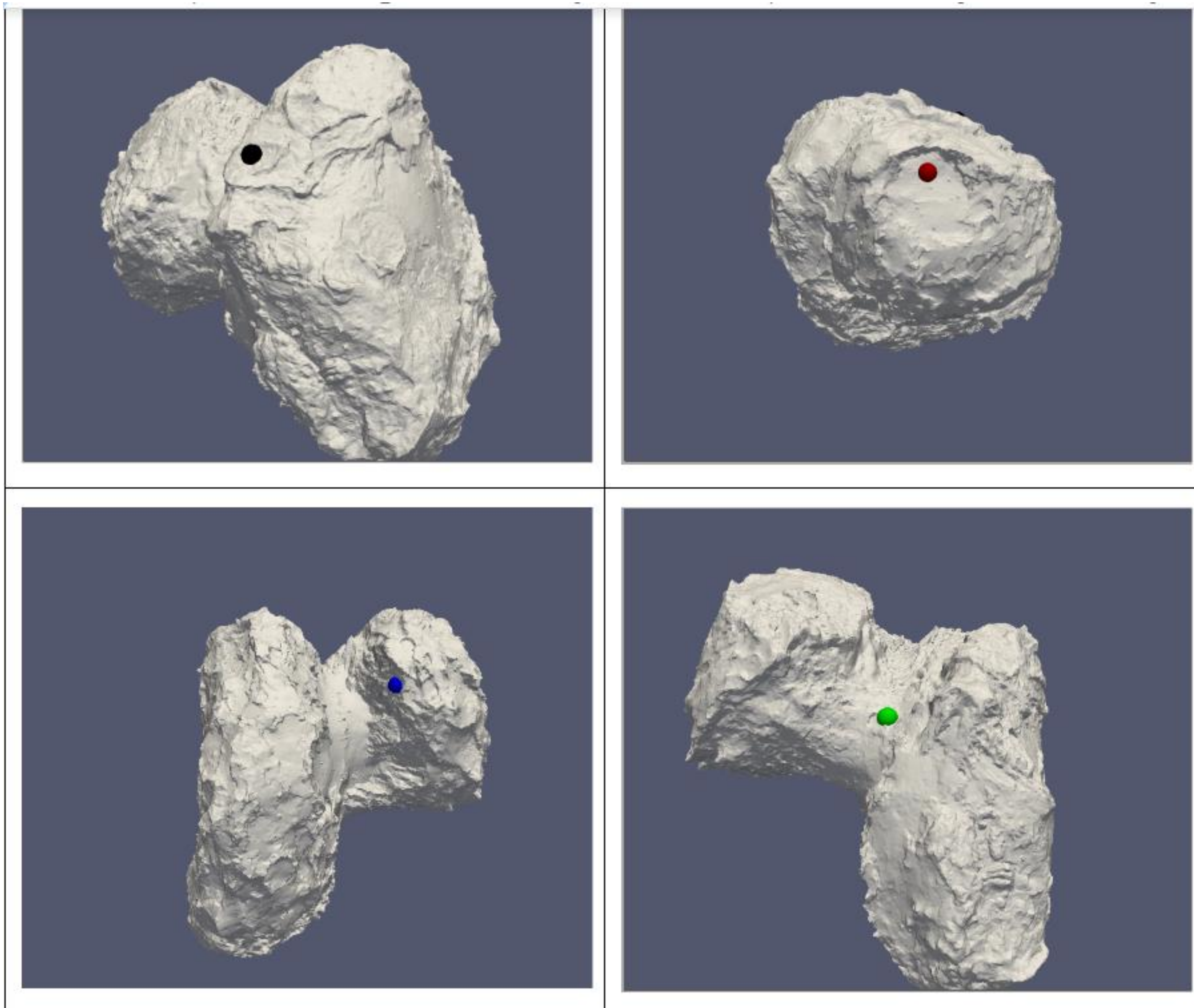


Fig. 2. Test points. Top: 1 and 2, bottom: 3 and 4.

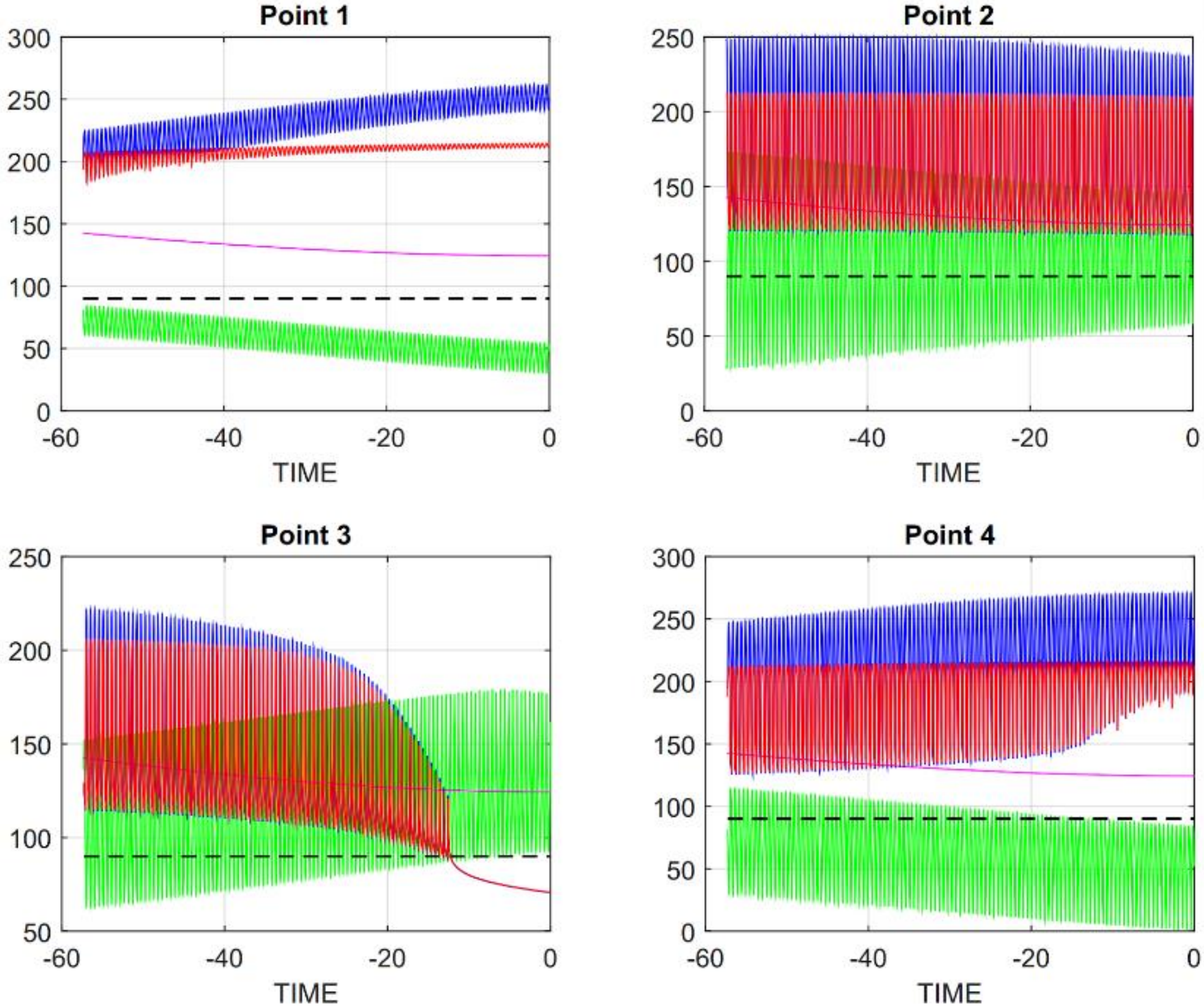


Fig. 3. Temperatures as a function of time for the surface (blue) and ice boundary (red). SZA (green) and heliocentric distance (magenta) are shown also.

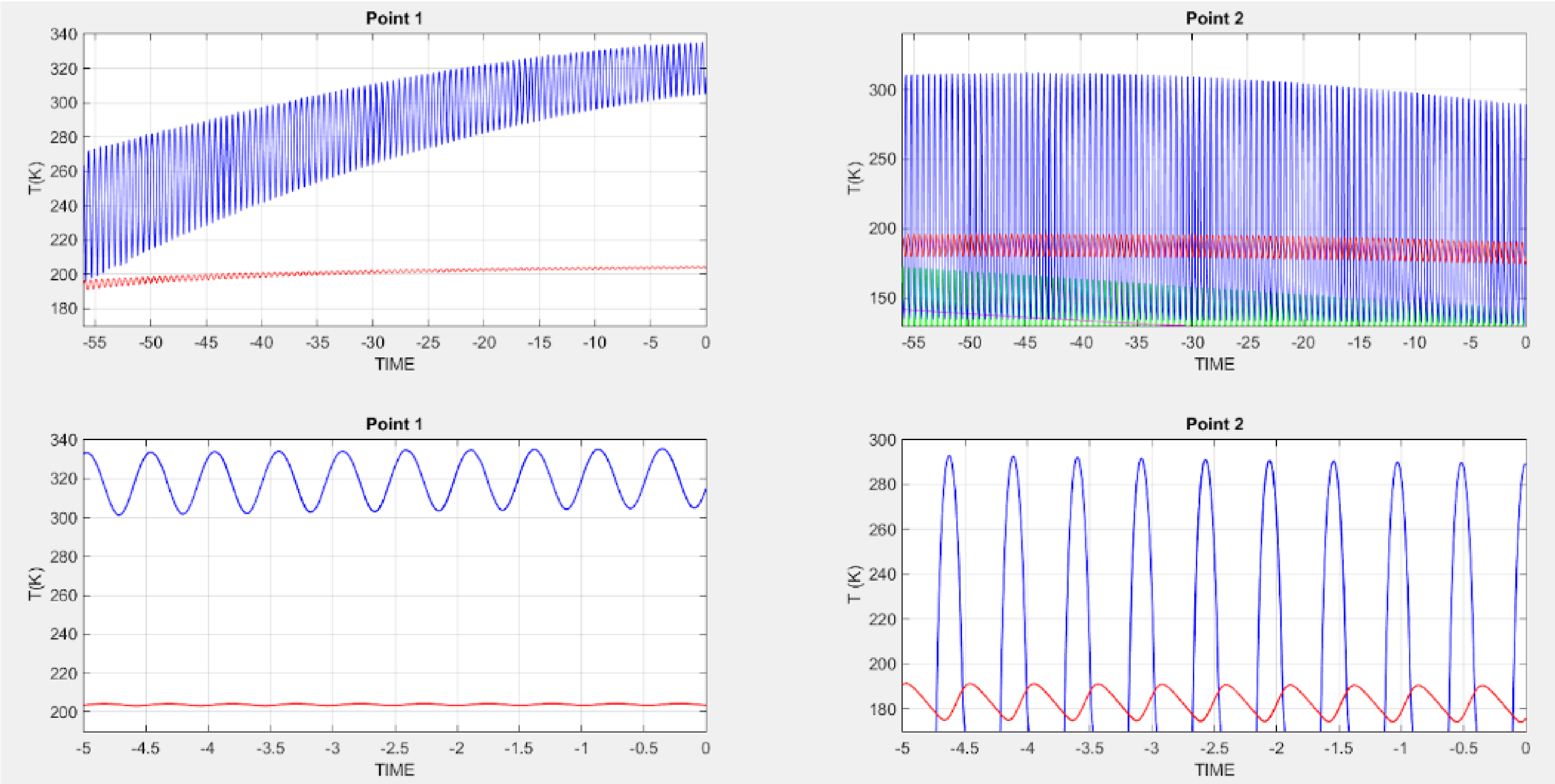


Fig. 7. Temperature as a function of time for two points (1 and 2) and one thicknesses of the dust layer (5cm). Relative thickness is 100 (permeability is ~2%). The surface temperature is shown in blue, the temperature of the ice boundary is red.

Conclusions

- The aim of our work was to accurately and systematically analyze the influence of various assumptions in thermo-physical modeling on the rate of change of the gas production of a comet.
- The recent Rosetta mission to 67P has brought a vast amount of unique data, making this comet a natural focus of our research.
- We analyzed the ***role of the nucleus shape and its rotation***, which is not typically known to such detail for other comets. However, our results pertain to this particular comet and it is not yet certain to which degree our findings can be generalized for other cometary nuclei.
- For comet 67P, the exact data available make our analysis more accurate, and the conclusions more rigorous.
- We examined the effect of several model assumptions, which are often used in cometary publications, in order to explain the **observed accelerated growth of gas production as the comet approaches the perihelion** (Keller et al. 2015a; Hu et al. 2017).
- In particular, we examined the effects of incorporating into consideration: – ***porous surface dust layer*** changing possible channels for utilization of absorbed solar energy; – *radiative heat conductivity*, which can be many times greater than the contact thermal conductivity in the case of dust particles of large size; – *factor of "ice area fraction",* which also modifies the energy balance at the icy interface.

- **Summarizing the results, we can conclude with certainty that the steep increase of the water production rate near perihelion of CG/67P (Hansen et al. 2016; Marshall et al. 2017) cannot be explained by a two layer model with a constant porous dust cover over the dust/ice matrix.**
- **Our calculations show that the activity level of the nucleus is not homogeneous or it is transient.**

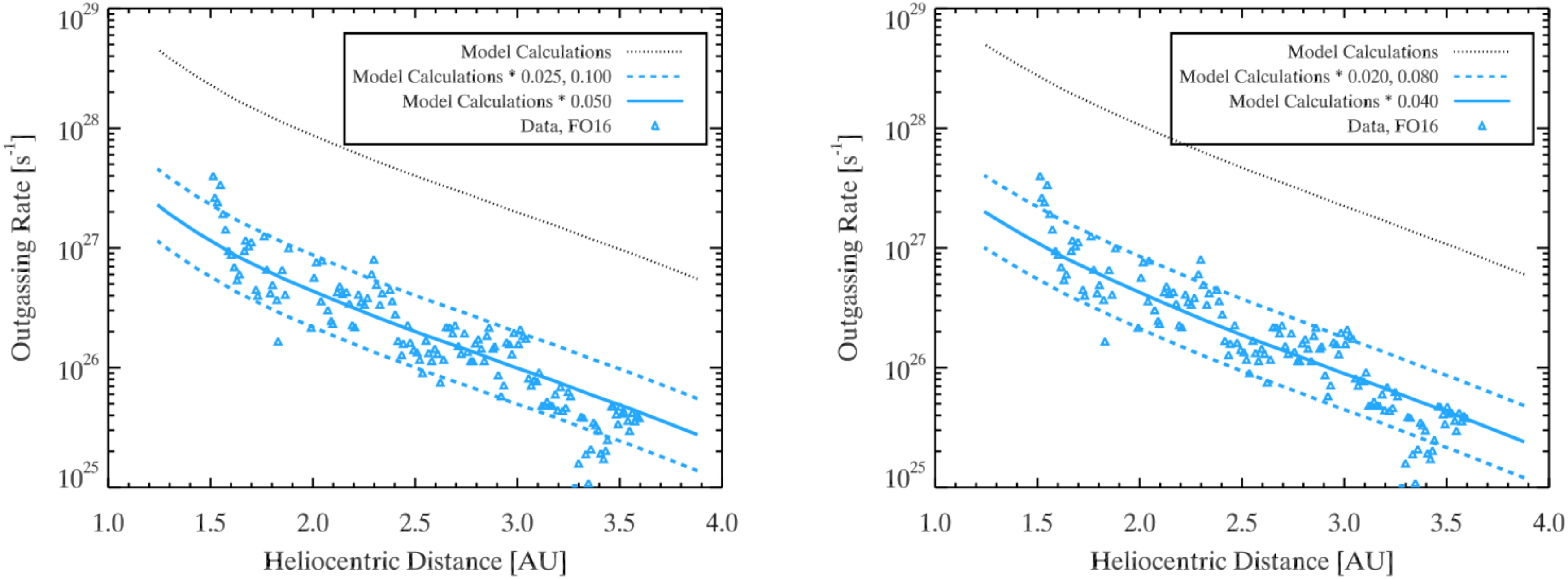


Figure 8. Water-vapour outgassing rates for comet 67P. Predictions of our thermophysical model (calculated for pebble radii of 5 mm) and an assumed dust-ice interface at 2 pebble radii (i.e. 1 cm) depth for the 67P outgassing rates of water ice (black dotted curves) and the measurements by Rosetta/ROSINA (Fougere et al. 2016) (triangles) are shown as a function of heliocentric distance. The solid and dashed blue curves denote models with different areal water-ice coverages at the dust-ice interface. Left: for a shape model of 67P consisting of 5000 facets and the obliquity of 67P and water-ice coverages of (from bottom to top) 2.5%, 5% and 10%. Right: for a spherical comet consisting of 1000 facets with no obliquity and water-ice coverages of (from bottom to top) 2%, 4% and 8%.

Evidence for the formation of comet 67P/Churyumov-Gerasimenko through gravitational collapse of a bound clump of pebbles

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