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Constraints on the activity of MBC 133P/Elst–Pizarro from a thermophysical perspective

Liang Liang Yu (1) & Wing Huen Ip (1,2)
(1) State Key Laboratory of Lunar and Planetary Sciences, Macau University of Science and Technology, Macau, China (yullmoon@live.com)
(2) Institute of Astronomy, National Central University, Jhongli, Taoyuan City 32001, Taiwan

Abstract

133P/Elst–Pizarro (hereafter 133P) is the firstly recognised main-belt comet. Previous observations show that it can be active for the $\sim 1/4$ of the orbit around post-perihelion. Here we use thermophysical model to explain the observations, which provides some constraints about the thermal environment and gas production of 133P. We find that it is not likely to explain the observed activity of 133P by a sublimation model of homogeneous buried ice layer. We thus propose that sublimation of regional surface ice patch may be responsible to the observations. In addition, the observed dust tail indicates the sublimation temperature of the icy patch to be 165 K at least. The temperature of the icy patch should have a significant seasonal variation, because the observed activity shows seasonal variation as well. This kind of seasonal variation could provide us constraints about the possible location of the surface ice patch and orientation of the rotation axis of 133P, but still could not obtain unique solution yet. More observations that can tell us when or where 133P is most active or observations that can determine the the orientation of 133P's the rotation axis are necessary.

1. Introduction

133P is a small body, whose orbit well keeps it in the main asteroid belt. It looks like an asteroid at most locations of its orbit, by also displayed a dust tail like a comet when it was near perihelion in 1996, 2001, and 2007, which leads to the discovery of a new comet group, named "Main-Belt Comet" (MBC), and hence 133P become the firstly recognised MBC. The discovery of MBCs implies that water ice can survive in the main belt even today. Details of the physical properties of the MBC nuclei can give us key information about the formation and evolution of the main belt, and hence provide clues about the formation and evolution of the solar system, and also tell us the origin of water on terrestrial planets like our Earth.

However, distances to MBCs are too far away for current telescopes to figure out what happens on such MBC nuclei. So spacecraft mission to MBCs would be necessary and meaningful. Then 133P becomes the target of a proposed ESA spacecraft mission named "Castalia", and it was also selected to be one of targets of a proposed Chinese small-body mission. Thus theoretical modelling and constraints about the thermal environment and thermal activity prior to the space mission would be of significance for both the mission planning and instruments design. Here we present some work in progress about the constraints of 133P's thermal environment and gas production relevant to its observed activity.

2. Model Results

2.1. Previous Observations

[1, 2, 5] reported optical photometry of 133P along its orbit, showing that activity can appear between Mean Anomaly $\sim -5.4^\circ$ and $\sim 74^\circ$, as shown in the Figure 2 of [5]. [1] found that the tails are mainly dust particles with radius $\sim 10\ \mu m$. The estimated tail mass-loss rates $\sim 0.016\ \mathrm{kgs}^{-1}$ at around November and December, 2002, indicates a water gas production rate $\sim 0.003\ \mathrm{kgs}^{-1}$ ($\sim 10^{23}\ \mathrm{s}^{-1}$), if assuming a dust-ice mass ratio $6:1$ like that of 67P. Such gas production rate is far weaker that $\sim 10^{26}\ \mathrm{s}^{-1}$ of a typical JFC like 67P at a same helio-centric distance ~ 3 AU [3], indicating the existence of dust mantle on the surface, thus lowering down the gas production rate. But questions about how and where the gas are produced from the nuclei of 133P, namely whether the gas are produced by sublimation from homogeneous buried icy layer or only from regional surface icy patch, are still unsolved.

2.2. Homogeneous buried ice layer?

If assume that 133P is homogeneous two-layer system with a dust mantle covered a dust-ice mixture interior. The thickness of the dust mantle should be ~ 50 to 150 m if 133P has stayed in the main belt over the entire lifetime of the Solar System according to [4]. For such a two layer system, the "two layer sublimation model" build in [6] can be well applicable. But if 133P is newly formed fragment of a larger icy parent object, then the icy layer can be more close to the surface, and hence the dust mantle can be much thinner. The question is how thin the dust mantle could be in a view of homogeneous distribution?

If we expect the existence of a stable dust mantle on 133P, the dust mantle thickness is then expected to be several seasonal thermal skin depth. As a simple case, let assume the axial tilt of 133P to be about $\pm 45^\circ$, then the seasonal equilibrium subsurface temperature $\tilde{T}_0$ and corresponding ice sublimation front temperature T_i at each local latitude can be estimated, as shown in left panel of Figure 1.

The seasonal equilibrium subsurface temperature $\tilde{T}_0$ indicates a thermal conductivity of $\kappa \sim 1.5 \times 10^{-3}\ \mathrm{Wm}^{-1}\mathrm{K}^{-1}$, a specific heat capacity of $c \sim 500\ \mathrm{Jkg}^{-1}\mathrm{K}^{-1}$, and hence a thermal diffusivity $\alpha \sim 1.15 \times 10^{-9}\ \mathrm{m}^2\mathrm{s}^{-1}$ if assuming a porosity $\varphi \sim 0.5$ and mass density $\rho \sim 2600\ \mathrm{kgm}^{-3}$ of the dust particle in the dust mantle. Consider the orbit period ~ 5.62 yr of 133P, the seasonal thermal skin depth would be

$$l_{\mathrm{sst}} = \sqrt{\alpha \frac{P_{\mathrm{orb}}}{2\pi}} = \sqrt{\frac{k}{(1-\varphi)\rho c} \frac{P_{\mathrm{orb}}}{2\pi}} \sim 0.2\ \mathrm{m}.$$

Then let's assume the thickness of the dust mantle to be

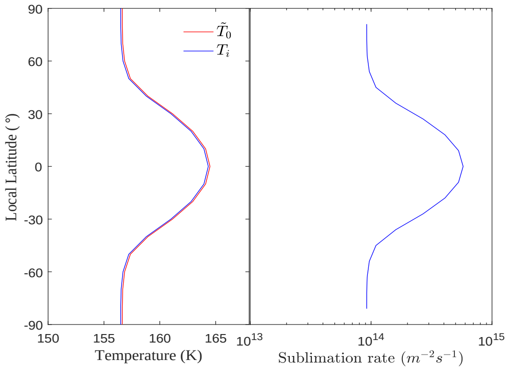

Figure 1: Left panel: Equilibrium subsurface temperature $\tilde{T}_0$ of the dust mantle and the ice front temperature T_i at each local latitude. Right panel: sublimation rate of water ice below each latitude.

0.5 m. The "two layer sublimation model" can still be a good approximation. The right panel of Figure 1 presents model estimated water sublimation rate of the ice front below each local latitude, ranging from $10^{14}m^{-2}s^{-1}$ to $6\times10^{14}m^{-2}s^{-1}$, indicating a total water gas production rate only $\sim 10^{20}s^{-1}$, which is far lower than the estimated production rate from observation. Besides, the sublimation rate $\sim 6\times10^{14}\ \mathrm{m^{-2}s^{-1}}$ is too weak to drag away dust particles with radius ~ 1 to $10\ \mu\mathrm{m}$ from the nuclei of 133P (radius ~ 1.9 km).

On the other hand, even assume the the total water gas production rate $\sim 10^{23}\ \mathrm{s^{-1}}$ is generated by homogeneous sublimation of near-surface ice, the sublimation rate would be around

$$\sim \frac{10^{23}\ \mathrm{s^{-1}}}{4\pi R^2} \sim 2.2\times10^{15}\ \mathrm{m^{-2}s^{-1}},$$

which is still unable to drag away $10\ \mu\mathrm{m}$ dust particles, because a sublimation rate of $\sim 10^{19}\ \mathrm{m^{-2}s^{-1}}$ is needed to to drag $\sim 10\ \mu m$ dust particles away from the nuclei of 133P. Thus this kind of homogeneous sublimation is likely to be responsible for the observed activity, and hence ice much more close to the surface is necessary to explain the observations.

2.3. Regional surface ice patch?

So if we expect near-surface ice to explain the observations, the sublimation rate $\sim 10^{19}\ \mathrm{m^{-2}s^{-1}}$ that can blow away $\sim 10\ \mu m$ dust particles indicates a sublimation temperature ~ 165 K of surface ice. And the sublimation area that accounts for the total production rate $\sim 10^{23}\ \mathrm{s^{-1}}$ would be about $10^4\ \mathrm{m^2}$, equal to circular region with diameter ~ 110 m, which is actually a rather small region compared to the whole surface of 133P.

So we are expecting that 133P has been in is orbit for a long time, making that the icy layer is deeply buried below most of the surface. But there may exist a small region that the previous buried ice is exposed to the surface due to some reason like impact. The exposed icy patch can be active enough to blow away $\sim 10\ \mu m$ dust particles, generating dust tails as the observation. The strong sublimation on the ice patch can blow away most dust particle, causing a moving boundary and hence preventing the formation of a stable dust mantle. In this way, the current observation can be well explained.

Now the question is where the exposed icy patch can be on the surface? Previous observations show that 133P can be active between Mean Anomaly $\sim -5.4°$ and $\sim 74°$, nearly $1/4$ of the orbit around post-perihelion, showing significant seasonal effect. So we expect that the temperature of the surface icy patch should keep larger than 165 K for this $1/4$ of the orbit around post-perihelion, but become lower than 165 K for the rest of the orbit. Temperature on different local latitude can show different seasonal variations, as the result of some particular orientation of rotation axis with respect to the orbit, which thus provides us a way to investigate the possible location of the surface icy patch and orientation of the rotation axis.

However, we can not yet remove the degeneracy of the location of the surface icy patch and the orientation of the rotation axis with the current knowledge of seasonal effect, because we actually do not know the maximum sublimation temperature and where it would appear during the active period. So we are not able to get unique solution about the possible location of the surface icy patch and the orientation of the rotation axis simultaneously at present. And thus we are expecting more observations that could tell us when or where 133P is most active, or directly give us the orientation of the rotation axis by other method like light-curve inversion method.

3. Discussions and Conclusions

At present, by using thermophysical model to explain current observations, we tend to believe the activity of 133P is generated by the sublimation of a surface icy patch exposed by impact rather than by the sublimation of homogeneous buried ice layer. The seasonal variation of activity indicates that temperature of the ice patch should also has a significant seasonal variation. To figure out where the icy patch could be on the surface, we need more observations, for example, observations that can tell us when or where 133P is most active, or observations that can directly work out the the orientation of 133P's rotation axis.

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