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Can a cometary mechanism explain the activity of the Geminids Parent (3200) Phaethon?

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Abstract

(3200) Phaethon is believed to be the parent of the Geminids, but the mechanism of mass loss has long been a mystery. By using a "dust-ice" two-layer model, we find that a cometary mechanism can explain the observed activity of (3200) Phaethon as well as its connection to the Geminids.

1. Introduction

The Near-Earth object (3200) Phaethon has been found to show similar orbit to those of Geminid meteoroids, and their orbits cross at their perihelion, indicating that Phaethon may be the source of the Geminid meteor stream, with some of the meteoroids being ejected from Phaethon at its perihelion during the past $\sim$ 1000 years [1]. If true, Phaethon would have had a comet-like activity, at least for the past millennium. However, over the next two decades after the discovery of Phaethon, people still have not observed a gas coma or a dust tail around Phaethon, until 2013, comet-like dust tails were observed during three perihelion passages in 2009, 2012 and 2016, respectively [5, 2]. In all the three cases, the tail appeared at Mean Anomaly $= 0^\circ \sim 1^\circ$ and continued for a very short time of $\sim$ 2 days [3]. The recurring of the tail at perihelion implies that it should have a periodic cause associated with the asteroid's orbital position. However it is not likely for Phaethon to retain near-surface volatiles for a long time because of its periodically high surface temperature as high as $\sim$ 1000 K at perihelion, thus raising questions about the mechanisms for continued significant mass loss from Phaethon.

In our recent paper [6], we proposed a "dust-ice" two-layer model to explain how Phaethon could provide the Geminids and the recent observed dust tails during its perihelion passages. Here in this abstract, we briefly introduce our major results and conclusions of paper [6].

2. Model Results

Considering the current orbit of Phathon in our long-term sublimation model of the dust-ice two-layer system, we find that the equilibrium temperature $\tilde{T}_0$ of the sub-surface dust mantle is about 300 K, while the ice sublimation front temperature T_i is much lower about 210 K (Figure 1), indicating that the time scale to lose all ice in current orbit is about 6 million years (Figure 2). Thus it is totally possible that Phaethon could still have ice retained inside.

In addition, since no gas coma has been detected by ground base telescope, the total water gas production rate should be smaller than 3×10^{25} s^{-1}, indicating the dust mantle thicker than 15 m at least (Figure 3). Moreover, we find that the time scale for the dust mantle to grow from 1 meter to 20 meter is about 1000 years. So, if consider an ideal case, the current dust mantle is about 15 m, it is possible that the dust mantle thickness could be smaller than 1 meter, 1000 years ago. And the corresponding total water gas production rate can be as large as 10^{27} s^{-1}, being as active as a common comet. Therefore, the Geminid meteor stream can be supplied by cometary mechanism during the past 1000 years.

On the other hand, as the combination results of the current orbit and rotation state, Phaethon suffers high temperature

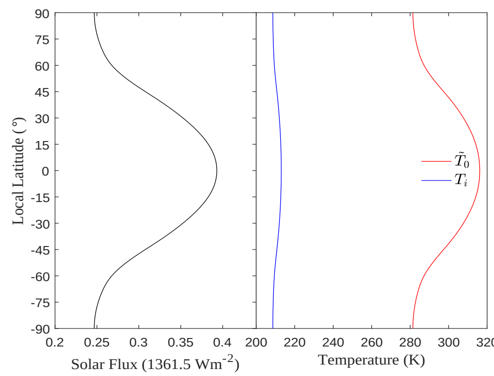

Figure 1: Left panel: Annual mean solar insolation as a function of local latitude on Phaethon; Right panel: Equilibrium subsurface temperature $\tilde{T}_0$ and ice front temperature $T_{\rm i}$ of Phaethon, assuming a geometric Albedo of $p_{\rm v} = 0.122$.

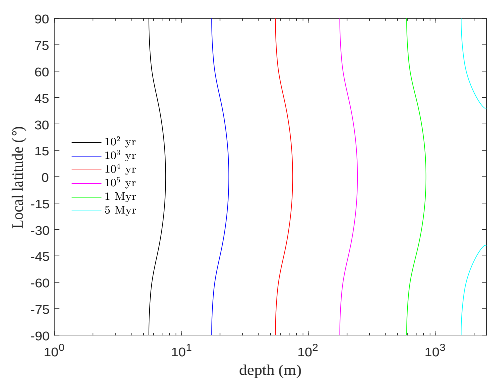

Figure 2: Phaethon: Secular inward motion of the ice front.

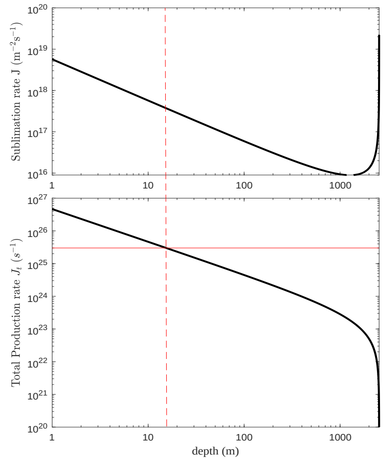

Figure 3: Phaethon: Upper panel: Sublimation rate J at the ice front as a function of the depth to the ice sublimation front; Lower panel: Total production rate J_t.

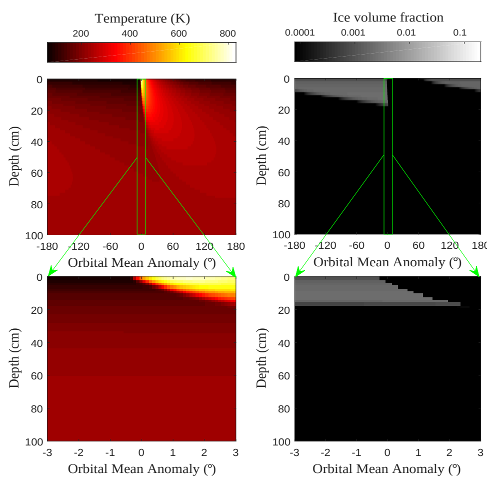

Figure 4: Simulation of a Sublimation/condensation cycle on the South pole of Phaethon. The initial ice/dust mass ratio χ_0 is assumed to be 0.15 (corresponding to initial ice volume fraction ~ 0.3) and the assumed dust mantle thickness $h_{\rm i} =$ 15 m.

variations > 600 K near perihelion, which could generate enough thermal stress to produce dust particles from rocks or boulders. The more interesting thing is the temperature at the South polar region, which will be sufficiently high to drive sublimation only between about $0°$ and $60°$ mean anomaly, equivalent to $\sim 1/6$ of the orbit. For the other $\sim 5/6$ of the orbit, the surface temperature keeps lower than 100 K (Figure 4). Any out-flowing gas will condense in a near-surface layer of $\sim l_{\rm sst}/5 \approx 20$ cm thickness, and the condensed ice will reach a volume fraction of $\sim 0.2\%$, there. We further find that the condensed ice will be quickly sublimated near perihelion within $\sim 1/180$ of the orbital period (~ 2.9 days). This transient sublimation pulse can generate a comparatively large gas outflow. Thus dust particles with typical size of Geminids particles can be blown away during perihelion passage only, for Mean Anomaly between $0°$ and $2°$. This is consistent with observation, since the dust tails reported by [5, 2] appeared at Mean Anomaly between $0°$ and $1°$ and lasted only ~ 2 days.

3. Conclusions

On the basis of our modeling:

(1) It is possible, for present-day Phaethon, to still retain buried water ice in its interior; the dry dust mantle should have a thickness of > 15 m at least. Sublimation of the buried ice is too weak to generate a coma observable with present ground-base instruments.

(2) It is possible, 1000 year ago, Phaethon's dust mantle could have had a thickness < 1 m, which would have allowed Phaethon to be sufficiently active to supply the Geminid stream up to the present.

(3) A significant sublimation/condensation cycle is predicted for Phaethon's south polar region even today. The sublimation and condensation cycle would lead to transient gas outbursts during perihelion passage (Mean Anomaly between $0°$ and $2°$) capable of blowing away dust particles and explain the observed tail.

(4) The large temperature variation > 600 K near perihelion could induce sufficiently large thermal stress to cause fracture of rocks or boulders, being an efficient mechanism that produces dust particles on the surface to be then blown away by outflow gas to generate dust tail. But the time scale of such dust-producing process should be longer than the seasonal cycle of water sublimation and condensation, thus can dominate the appearance cycle of Phaethon's tail.

Of course, the proposed mechanisms need to be further examined by new observation and in-situ detection, especially precise constraints on the total gas production rate, from which we should be able to estimate how much ice Phaethon really contains. The proposed JAXA/ISAS DESTINY$^+$ mission to Phaethon would certainly bring new insight to understand the origin and evolution of Phaethon as well as its connection to the Geminid meteor stream.

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