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THERMAL PROCESSING OF JUPITER-FAMILY COMETS DURING THEIR CHAOTIC TRAJECTORIES

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Abstract. As evidenced by the existence of active objects at large heliocentric distances (e.g. Centaurs and long-period comets), thermal alterations can occur in the giant planet region, and beyond. In this work, we examine the long-distance and long-term activity of the population of Jupiter-family Comets (JFCs). We couple a thermal evolution model to a sample of JFC particles, tracked from the moment they enter the giant planet realm, and until their ejection from the Solar System. We identify a pattern of multiple, long-lasting heating episodes for all JFC particles, due to the stochastic nature of their trajectories. We study the effect of these episodes on the comets' internal structure and chemical composition. We report severe losses of primordial condensed hypervolatile content and alterations on the subsurface layers of several dozen to hundreds of meters. We demonstrate the necessity of studying the complete thermal and orbital history of JFCs, and comets in general, when interpreting current observations.

Keywords: Comets, numerical methods, comet dynamics, comet nuclei

1 Context

The journey of Jupiter-family Comets (JFCs) towards the inner parts of the Solar System is a chaotic and lengthy process. It is dominated by interactions with giant planets, through a series of close encounters that change drastically the orbital elements of JFCs as they roam the giant planet region, towards the positions where they are observed today (Levison & Duncan 1997). In this study, we investigate –from a theoretical point of view– the consequences of these chaotic trajectories on the evolution of JFC nuclei.

2 Methods

We propose a coupling between a thermal evolution model (Guilbert-Lepoutre et al. 2011) and a sample of 276 JFC particles' trajectories. These were obtained from long-term simulations of the dynamical evolution of the Solar System's small bodies, successfully reproducing the observed orbital distribution of JFCs (Nesvorný et al. 2017). A number of simplifying assumptions is adopted in order to achieve this coupling between evolutionary processes, with very different timescales, i.e. the orbital evolution on the one hand, with timescales of the order of hundreds to millions of years, and the thermal evolution on the other hand taking place on timescales of the order of minutes and hours (Prialnik et al. 2004).

3 Results

In Figure 1 (left panel), a typical JFC trajectory from our sample is presented. Extensive orbital changes are recorded, due to the close encounters with the giant planets, resulting in several approaches and retreats from regions of thermal interest, i.e. regions where alterations can take place. In the right panel of Fig. 1, where an example of the proposed coupling (albeit for a different particle) is given, these approaches and retreats, alongside with the induced internal temperature changes are highlighted. In this example, nine different approaches can

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be identified, resulting in the significant heating of an extensive subsurface layer. This pattern of intense heating periods, spread out randomly over a particle's lifetime, was observed with different frequency and magnitude in all the JFC particles of our sample. We underline that these heating episodes should not be confounded with the typical perihelion-aphelion passages or seasonal changes of a comet. To quantify the consequences of these episodes on a JFC nucleus, we follow three characteristic temperatures associated with well-known cometary activity mechanisms: a) 25 K for the sublimation of hyper-volatile species (such as CO), b) 80 K for the sublimation of moderately volatile species (such as CO_2) and c) 110 K for the amorphous to crystalline water ice phase transition. By tracking down the depths of these temperatures the moment our particles transition from Centaurs to JFCs we are able to get a first estimation of the level of thermal processing of a JFC. For the 276 particles of our sample, all with a 5 km-radius nucleus, the estimated average depths were: ∼4100 m for the 25 K isotherm, ∼125 m for the 80 K isotherm and ∼27 m for the 110 K isotherm. These depths indicate alterations deep within JFC nuclei, at a time much prior to their entrance in the inner parts of the Solar System where we usually observe them.

4 Conclusions

Our results indicate that a typically observed JFC is most likely a processed object. Although there is a certain number of limitations to our simulations (related to computational and numerical issues) it seems that primordial free condensed hyper-volatile material cannot survive these chaotic trajectories. Alterations for other species (such as moderately volatile species) are conceivable at substantial depths below the surface. They also suggest that the current activity of JFCs is produced from processed layers. This study highlights the necessity to consider both the thermal and dynamical history of JFCs, in order to interpret present observations.

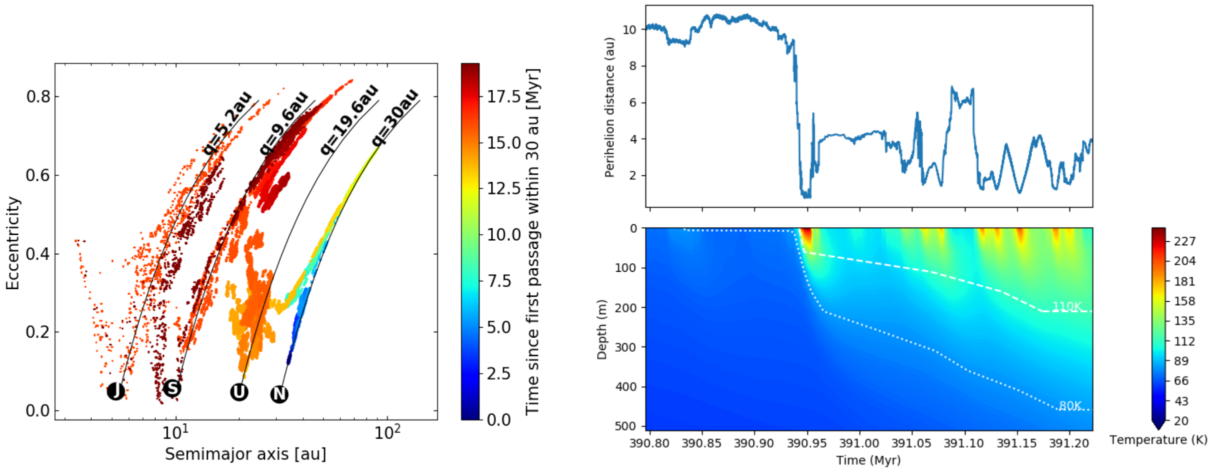

Fig. 1. Left: Example of a JFC particle's trajectory and orbital changes due to close encounters with the giant planets (marked with black circles). The color code gives the time evolution and total dynamical lifetime of the particle in the inner Solar System. **Right:** Example of the coupled thermal and dynamical evolution of a JFC particle. Upper panel: Averaged orbital evolution. Lower panel: Internal temperature distribution and corresponding heating episodes. The dashed and dotted lines represent the positions of the 110 K and 80 K isotherms.

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