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Orbital evolution of Centaurs and their transition to Jupiter family comets: implications for the onset of cometary activity

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Abstract

We have forward modeled the dynamical evolution of objects from the trans-Neptunian region, through the giant planet-crossing Centaur population, and into the Jupiter family comet population. Using this model, we have identified an important, short-lived transition phase in the orbital evolution of Centaurs that are transferred into the active comet population. This orbital transition is also associated with a transition in the thermal environment of small bodies. We will discuss this transition region in the context of current and future observations of activity in Centaur and comet populations.

1. Overview of the Centaur population

Centaurs are a transient population of icy bodies generally defined as having orbits with semimajor axes inside the orbit of Neptune ($a < 30.1$ au) and perihelion distances outside the orbit of Jupiter ($q > 5.2$ au), i.e. chaotic orbits that strongly interact with the giant planets [4]. These strong gravitational interactions limit Centaurs' dynamical lifetimes to timescales that are very short compared to the age of the solar system, on the order of $\sim 10^6 - 10^7$ years [9, 1]. Thus, the Centaur population must be resupplied with objects from the Trans-Neptunian region [2].

Most objects that enter the Centaur population will experience a gravitational perturbation with a giant planet that kicks it into the distant outer solar system, or ejected from the solar system entirely on a hyperbolic orbit. Nevertheless, approximately a third of Centaurs will dynamically evolve through the giant planet region to enter the Jupiter family comet (JFC) population. These are volatile-rich objects with perihelia in the inner solar system and aphelia near the orbit of Jupiter [9, 1].

Therefore, Centaurs are the dynamical link between trans-Neptunian objects (TNOs) and active JFCs and between the outer and inner regions of the solar system.

While Centaurs undergo this orbital evolution, they physically evolve due to their changing thermal environment. A subset of Centaurs are known to exhibit comet-like activity - Emitting gas and dust and sustaining a coma structure. This appears to correspond to objects with the smallest perihelia within $\sim$ 5-10 au from the Sun [5, 3]. Surface temperatures in this region are too low for water-ice to efficiently sublimate (the dominant source of activity for comets nearer to the Sun). Instead, observed Centaur dust comae may result from other thermal processes that are active at temperatures consistent with heliocentric distances out to $\sim$ 10 au. Such processes can be the crystallization of amorphous water ice, which can release trapped volatile species, such as CO and CO_2, or triggering of sub-surface insulated ice patches [10].

2. A detailed dynamical study of Centaurs and the transition to the JFC population

To study the characteristics of Centaurs that become JFCs, we have taken a forward modeling approach. We start with a population of TNOs in the outer solar system,and integrate their orbits forward in time to track their dynamical evolution into and through the Centaur region (and later into the inner solar system). The initial conditions for our simulations are based on the population of scattering TNOs [6, 8], as well as the dynamically excited portion of the classical Kuiper belt [7]).

We track the orbits of these test particles as they evolve inwards. Orbital changes occur very quickly once Centaurs evolve onto orbits in the Jupiter and Saturn region, so we track orbits of evolving particles at increasingly frequent time intervals. This is apparent in Figure 1, which shows the average time a test particle in the Centaur population spends at various combinations of semi-major axis and eccentricity.

Using these detailed simulations, we can identify important transition points in orbital evolution for Centaurs that eventually migrate into JFC orbits interior to Jupiter.

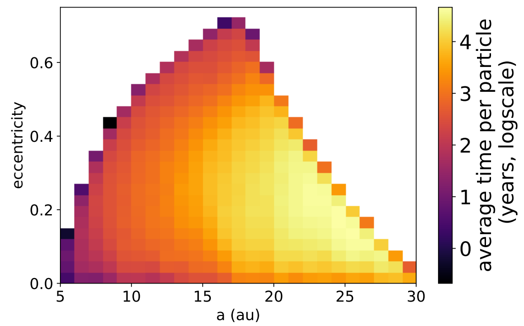

Figure 1: The average time Centaurs with orbits entirely within the giant planet region (perihelion $q > 5.2$ au and aphelion $Q < 30$ au) spend at different semimajor axis and eccentricity combinations.

3. Implications for studying the physical transition from Centaurs to JFCs

Our detailed numerical study can help us understand the onset of cometary activity in small bodies,a s their orbits change. We can achieve this by analyzing our orbital evolution results, which connect Centaur to JFC orbits, in conjunction with observations of activity in specific Centaur objects.

The Centaurs that become JFCs in our simulations pass through specific orbital phase space regions. These correspond to important orbital transitions and that are also likely to correspond to changing thermal environments. We will discuss this orbital transition to the JFC population, the number of observed objects we expect to currently be in this transitional orbital state, and how this relates to activity.

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