Analyzing the dynamics of centimeter to kilometer-sized bodies on JFC-like orbits P. M. Shober[1], J. Vaubaillon[1], G. Tancredi[2], H.A.R. Devillepoix[3,4], E.K. Sansom[3,4], S. Deam[3], S. Anghel[1,5], F. Colas1, S. Martino[2] [1]Institut de Mécanique Céleste et de Calcul des Éphemerides, Observatoire de Paris, PSL, 75014, Paris, France (patrick.shober@obspm.fr), [2]Departmento de Astronomía, Facultad de Ciencias, Iguá 4225, 11400 Montevideo, Uruguay, [3]Space Science and Technology Centre, Curtin University, GPO Box U1987, Perth WA 6845, Australia, [4]International Centre for Radio Astronomy Research, Curtin University, GPO Box U1987, Perth WA 6845, Australia, [5]Astronomical Institute of the Romanian Academy, Cutitul de Argint 5, 040557 Bucharest, Romania

Introduction: Jupiter-family comets (JFCs), a significant group within the comet population, are known for their short orbital periods and frequent close interactions with Jupiter. JFCs are icy bodies that originate from the outer solar system in the scattered disk and Kuiper belt. Their journey to the inner solar system is a chaotic and stochastic process controlled by close encounters with Neptune and Jupiter. Only a small portion of this source population in the outer solar system randomly walk their way into the inner solar system, and those that do, spend very little time there. Previous models of the population estimate that the dynamical lifetimes of JFCs are on the order of 10^5 yrs, whereas their lifetimes in near-Earth space only last a couple thousand years [1,2,3]. These frequent close encounters give the JFCs a characteristically short dynamic "memory", as shown by their concentration in Lyapunov lifetimes between 50-150 years [4]. These distinct dynamic characteristics of JFCs can be used as a discriminating factor to separate dark carbonaceous asteroids from the outer main belt from genetically cometary objects [5,6,7].

Despite this rarity of arrival in near-Earth space, many studies of observations from fireball networks claim to witness a significant portion of their observations originating from JFC-like orbits. The only study to use the dynamic stability of the orbits as a determining factor was by Shober et al. 2021 [7], as they found ~96% of the sporadic fireballs on JFC orbits observed by the Desert Fireball Network (DFN) were dynamically more consistent with main belt derived debris.

The primary aim of this research is to expand upon the analysis of Shober et al 2021 [7] and Fernandez & Sosa 2015 [6] by analyzing a large dataset of both JFCs and comet-like fireball observations. Our analysis will characterize the origins of objects from JFC-like ($2 < T_J < 3$) orbits at vastly different size scales, centimeter-meter versus kilometers in diameter. This consideration of a large variety of objects is crucial.

JFCs are believed to not only have short dynamical lifetimes in near-Earth space, but also short physical lifetimes due to cometary splitting and disintegration events. If this hypothesis is true we should see the debris from these splitting events greatly influencing the meteoroid populations being observed by fireball networks. Thus, in order to better understand the kilometer-scale comets and the meteoroid populations, we must consider them together. We can gain many more insights into the dynamic and physical evolution of these populations in this manner.

Methods: This research stands out for its extensive utilization of data from four major continental-scale fireball observation networks and its incorporation of ephemeris data of Jupiter-family comets (JFCs). In total, our extensive analysis includes 646 fireball orbits and 661 JFCs. This direct comparison of the dynamics of both meteoroid and comet populations has not been extensively explored in prior research.

The fireball data was taken from four continental-scale projects: the Desert Fireball Network (DFN), the European Fireball Network (EFN), the Fireball Recovery and InterPlanetary Observation Network (FRIPON), and the Meteorite Observation and Recovery Project (MORP), complemented by JFC ephemeris from the NASA HORIZONS database. Orbital stability analysis over 10,000-years, Lyapunov lifetime estimation, debiased NEO model source region estimation [8], meteorite fall identification, and meteor shower analysis [9] was conducted is order to characterize the results and determine whether the objects likely originated in the main-belt or in the outer solar system.

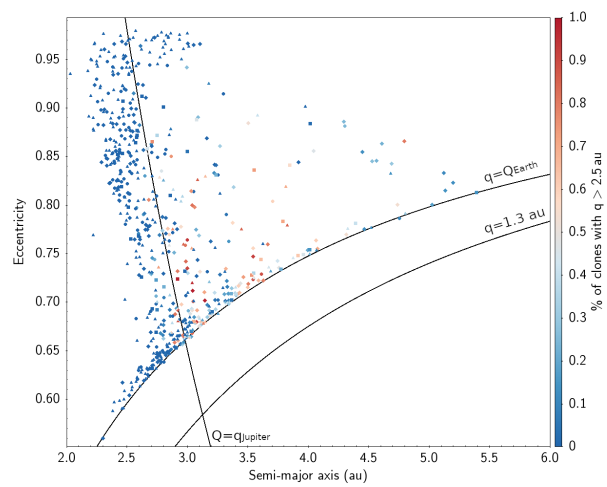

Figure. 1 Orbital distribution of 646 fireballs on JFC-like (2<TJ<3) orbits where the color indicates the percentage of clones that reach q>2.5 au orbits within our 10 kyr simulations

Results: In our study, we analyzed 646 fireball orbits and 661 JFC orbits, significantly expanding the dataset examined by Shober et al. (2021). This larger dataset enabled a more detailed investigation into the orbital stability of both fireballs and JFCs on 10,000-year timescales. Our findings reveal that a vast majority of meteoroids, even though on JFC-like orbits, do not dynamically align with the typical JFC population. In fact, most originate from stable orbits, with only 8-21% likely to have experienced close encounters with Jupiter. This implies that only 1-5% of all the fireballs being observed by these networks are genuinely JFC in origin. This directly challenges the notion put forward by Borovička et al. [10] that centimeter-to-meter scale meteoroids on JFC-like orbits predominantly originate from JFCs, a study that did not take into consideration the dynamics of the orbits observed, only the osculating orbits.

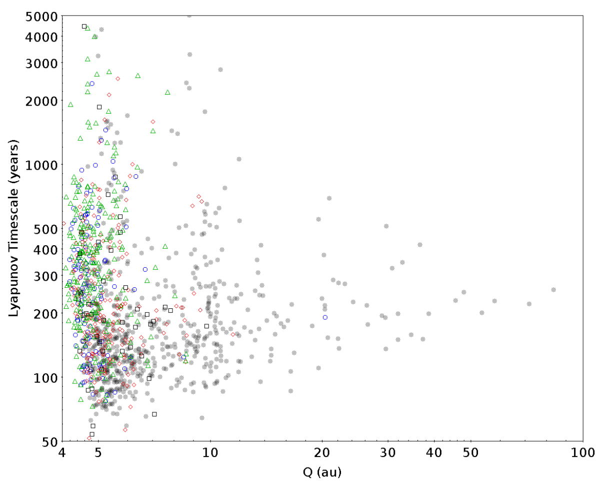

Figure 2 Lyapunov lifetime (inverse of Lyapunov exponent) versus the aphelion distance for DFN (blue), EFN (red), FRIPON (green), and MORP (black) data. Also the 661 JFCs are plotted as solid black points.

The analysis here of the orbital histories of 661 JFCs also reconfirms that most JFCs encounter Jupiter very frequently, leading to chaotic orbital behavior and limited predictability. Most JFCs also exhibit low Lyapunov lifetimes (100-150 years; Fig. 2), suggesting a limited dynamical memory due to the chaos in their orbits. However, a notable subset of 24 JFCs in near-Earth, active orbits (22 of which are NEOs) display exceptional orbital stability. These stable JFCs could be asteroidal interlopers from the outer main asteroid belt, rather than typical JFCs, which seldom spend extended periods in the inner solar system.

We also identified several meteor showers within the JFC-like subset across multiple fireball networks. Most of these showers and their associated parent bodies are in stable orbits, often protected from close encounters with Jupiter due to Kozai-resonance induced circulation of the argument of perihelion. Notably, the October Draconids, linked to comet 21P/Giacobini-Zinner, stand out for exhibiting typical JFC dynamics. Additionally, our use of the debiased NEO model [8] to estimate source regions indicates that the majority of meteoroids likely originate from main-belt sources, particularly from resonances such as the 2:1 and 11:5 MMRs.

The stability of meteoroid orbits, coupled with the Kozai-resonance effect, suggests a predominant influence of asteroidal material, particularly from the outer main belt, in the JFC-like meteoroid population. The diffusion of debris from the outer main-belt has been demonstrated to be possible in several previous studies [11,12,13]. Our findings highlight the complexity and diversity of the small-body environment in our solar system and challenge traditional assumptions about the origins of JFC-like debris observed on Earth.

Conclusions: Our study finds significant differences in the dynamics of kilometer-scale JFCs and centimeter-to-meter scale meteoroids. While JFCs frequently encounter Jupiter, resulting in dynamic and transient orbits, the meteoroids detected by fireball networks primarily originate from stable orbits. Only 8-21% of these meteoroids are likely to have had close encounters with Jupiter, suggesting their origins are not predominantly from JFCs but from more stable sources, likely the outer main asteroid belt.

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