Detections of Mini-Moon Fireballs within the Desert Fireball Network.

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Introduction: Objects that are captured by the Earth-Moon system are commonly called natural Earth satellites (NESs), temporarily captured orbiters (TCOs), or mini-moons. For most of the 20th century little work appears to have been done to characterize this hypothesized population. In 2006 the first Earth TCO was observed, 2006 RH120, in which it stayed in orbit around the Earth for 11 months [1]. At the moment, this is still the only TCO ever observed. Although, once the Large Synoptic Survey Telescope (LSST) starts operating in 2022, there could be a new TCO discovered every 4 days [2,3,4]. The TCO population is of vital importance for future space exploration, in-situ resource utilization and asteroid mining. TCOs are the most accessible objects in the solar system because they have the lowest delta-v required to reach. Additionally, they can provide key information about the smallest size fraction of the NEO population because most TCOs orbit multiple times before escaping [4], being readily observable for extended periods. The first model and attempt to characterize the TCO steady-state population was not until 2012 [5]. Based on current models, at any given time there should be a ~1m object captured by the Earth [5,6]. Around 1% of the TCOs eventually impact the Earth, and roughly 0.1% of meteors will have been captured by the Earth prior to impact. There has been only one fireball detected with a believed TCO origin: The European Fireball Network recorded an event which they published as having a 92-98% chance of being captured by Earth before detection [7]. Despite the capture percentage being very high, the capture duration for this meteoroid varied from 48 days up to over 5 years [7]. Satellite capture and capture duration highly unpredictable due to the fractal nature of the source space [8,9,10]. This results from the capture region being on the boundary of two adjacent sinks, and is thus inherently chaotic since small changes in the initial conditions lead to different trajectories [8]. To date, current models assume that the orbit-density distribution is independent of the size-frequency distribution [5,6]. The DFN is particularly ideal for checking the validity of this assumption due to the high precision in the orbits and the size of the fireball orbital dataset. Obtaining accurate models and understanding the typical trajectories taken by these objects in vitally important to making the detection and tracking of these objects more efficient and frequent.

Methods: The Desert Fireball Network has a network of over 50 photographic observatories throughout Australia that cover about 2.5 million km^2 of land [11]. The data collected from this network is processed automatically by an autonomous data reduction pipeline. The orbital integration within this study was done using Rebound and Reboundx [12,13]. Non-gravitational forces were primarily added through Reboundx and include: radiation forces, gravitational harmonics, and atmospheric drag. The atmospheric drag at the beginning of the fireball trajectory is accounted for using the NRLMSISE-00 model 2001 ported to Python based off of Dominik Brodowski 20100516 version (http://www.brodo.de/english/pub/nrlmsis/). The atmosphere integration was performed several times varying the mass-estimation method, the shape, and the density. The resulting top-of-the-atmosphere particles are then integrated back until they escape the Earth-Moon system. Particles are considered captured if they have a planetocentric Keplerian energy < 0 and are within 3 Hill radii [5,10]. Although, to be considered a TCO, the particle must make at least one complete orbit around the planet. Once all the particles have escaped or impacted, the integration is then done going forward in time, this time using the Earth-Moon barycenter model. This was done to see how influential the Moon was on the capture and impact probabilities.

Observations: The DFN has observed two fireballs with possible TCO origin to date. Event DN160822_03 which fell in South Australia, near to Lake Frome is described in Figs 1-3, and has the best data and the highest probability of being captured prior to impact of the fireballs analyzed.

Results: The fireball DN160822_03 was then modeled using the technique described above. Fig 4 and 5 show preliminary trajectory predictions:

Conclusions: Currently there are two events within the DFN orbital dataset that may have been captured prior to impact. Given that the DFN dataset contains 1000+ events, this would be indicative that about 0.1-0.2% of fireballs observed by our network are TCO impactors. This value corresponds very well to the value of 0.1% predicted by models [5]. The capture probability and capture period although for the events is highly dependent on the initial velocity and the triangulation method. This is entirely reasonable due to the fact that the source region for the TCOs is chaotic in nature and predicting it's pre-impact trajectory is very difficult.

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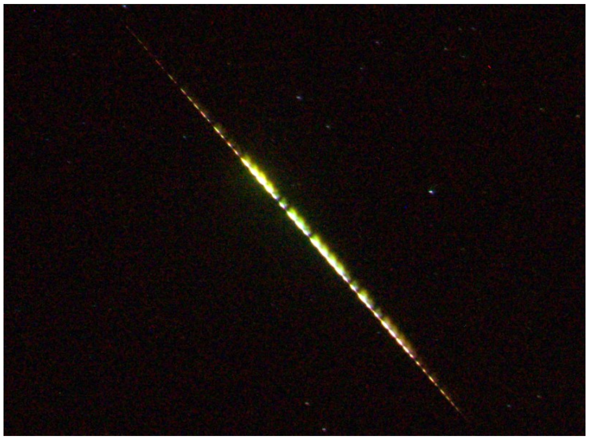

Figure 1. Photographic image taken of extremely slow fireball event DN160822_03 by the Wertaloona station in South Australia.

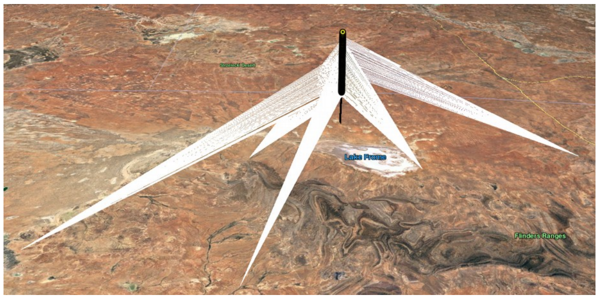

Figure 2. Triangulated trajectory of fireball over South Australia. During 5.32 sec luminous phase using data collected from 6 cameras.

Slope	86.56 °
Duration	5.32 sec
Best Convergence Angle	87.84 °
Number of Cameras	6
EKF Initial Velocity	10931.34 m/s
EKF Final Velocity	3901.84 m/s
EKF Initial Mass	1.64 kg
EKF Final Mass	0.02 kg

Table 1. Event DN160822_03 description.

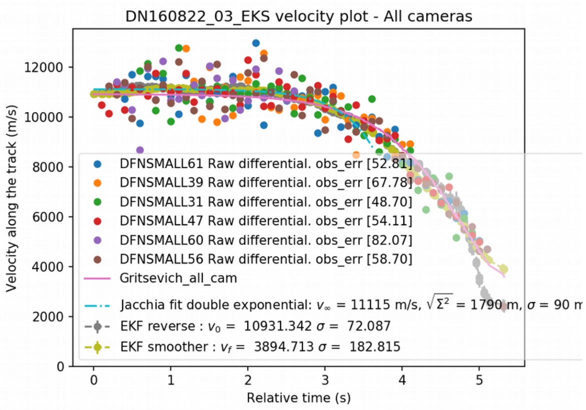

Figure 3. Velocity scatter plot with Extended Kalman Filter (EKF) model fit. Initial velocity was 10931.342 m/s observed at 74.078 km altitude. No apparent fragmentation occurred during the very steep impact (86.56 °).

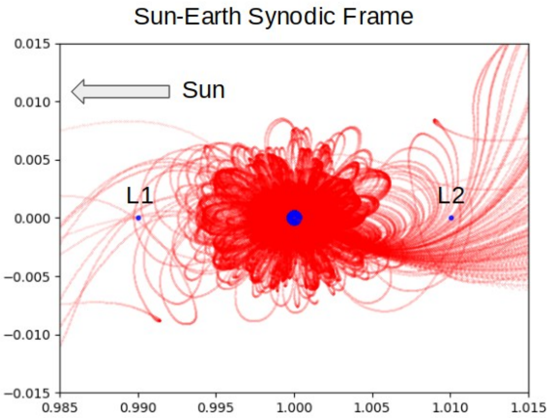

Figure 4. Paths of captured particles in the synodic frame, all particles seem to preferentially be captured through the first and second Lagrange points.

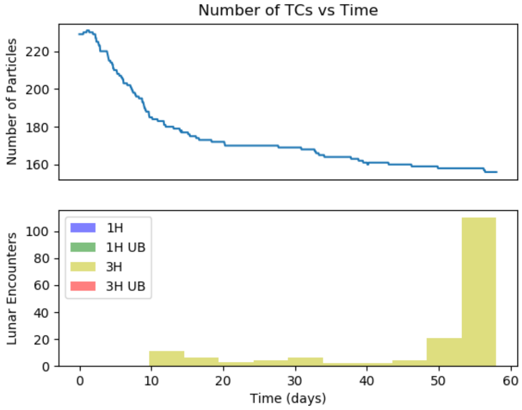

Figure 5. Preliminary results showing the number of temporary captures (TC) and lunar encounters as a function of time. Lunar encounters are grouped by distance in lunar Hill radii and whether or not the particles are unbound or not.