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The dynamical behaviour of the Chelyabinsk superbolide by using a Runge-Kutta algorithm

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Abstract

Our research group has started a special program to study the dynamical properties of meteoroids ablating in Earth's atmosphere. By using typical approaches about the drag and mass loss equations we have developed a Runge-Kutta algorithm capable to provide valuable ablation and bulk physical parameters of recorded fireballs. Using this approach, some results on the deceleration and relative mass loss of the Chelyabinsk superbolide occurred on Feb. 15th, 2013 are presented.

1. Introduction

On Feb. 15th, 2013 our current view about impact hazard was seriously challenged. While everybody was happy for being able to forecast the close approach of NEA 2012DA NEA within a distance of 27,700 km, an unexpected impact with an Apollo asteroid happened. At 03:20 UTC a superbolide overflew the Russian territory, concretely the region of Kazakhstan. The possible link between the superbolide and the 2012DA NEA was discarded by ESA and JPL-NASA from the reconstruction of the incoming fireball trajectory. The Chelyabinsk superbolide entered in the atmosphere at ~68,000 km/h and according to the DoD satellite images and infrasound data the maximum brightness occurred at an altitude of 23.3 km with a velocity of 18.6 km/s [1]. Fortunately, many casual videotapes of the bolide trajectory from the ground were obtained due to the nowadays common dash-cams available in private cars. According to the videotapes available it is possible to study this event as never before, and allowed the reconstruction of the heliocentric orbit in record time [2-4].

Our group is currently developing different applications to study in deep detail the dynamical behavior of videotaped bolides. The possibility of studying superbolides as the one occurred in Chelyabinsk is a very attractive milestone to be considered. The software that is being developed by first author in the framework of his master thesis is being tested by several cases discussed in [5] and also using events from the 25 video and all-sky CCD stations set up over the Iberian Peninsula by the SPanish Meteor Network (SPMN).

2. Dynamical behaviour

The motion and the ablation of a non-fragmentating meteoroid during atmospheric flight can be described by the drag and mass loss equations presented by Bronshten [6]:

$$\frac{dv}{dt} = -K \cdot \rho_{air} \cdot m^{-\frac{1}{3}} \cdot v^2 \qquad (1)$$

$$\frac{dm}{dt} = -\sigma \cdot K \cdot \rho_{air} \cdot m^{-\frac{1}{3}} \cdot v^3 \qquad (2)$$

Many authors suggest that these equations cannot be used for cases where abrupt fragmentation takes place. However they can be applied in different parts of the trajectory where no disruption happens. We have tried to do that for the ending part of Chelyabinsk trajectory, just after the main fragmentation. From the dash-cam casual videotapes we reconstructed the trajectory, velocity and altitude of the superbolide. We have used the equations (1) and (2) to reproduce possible solutions adjusting the values of σ and $K \cdot m_o^{-1/3}$ the ablation coefficient and the product between the mass and the shape-density coefficient respectively in a similar way was performed previously [7]. To perform the integration of the ordinary differential equations the Runge-Kutta method has been used with a stepsize of 150 m. The first picture shows the direct result obtained by the equation of the evolution of the velocity in function of the altitude the curve is the closest solution to the data points present with circles. Fig. 1 plots the velocity as a function H(km) provided from a videotape analysis made by Esko Lyttinen.

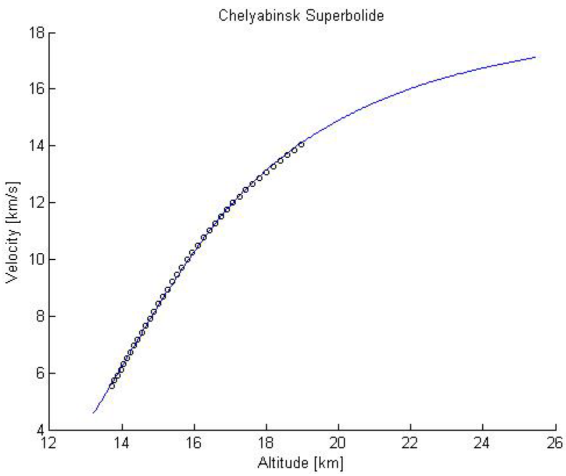

Figure 1: Measured velocity of the Chelyabinsk bolide (dots) and the obtained Runge-Kutta fit.

According to the JPL/NASA press release the maximum brightness was achieved at an altitude of 23.3 km (Fig. 2). This is consistent with our results as the maximum inferred value of mass loss rate from our dynamic data occurs at an altitude of 23.5 km (Fig. 3). It is well-known that the maximum brightness is produced shortly after the meteoroid breaks apart in being exposed the fragmented/pulverized material to the heat propagated by the shock thermal wave located in the meteor head (Fig. 2).

Figure 3. The superbolide ending path and its overwhelming flare at ~23 km from the surroundings of Chelyabinsk. Courtesy of Marat Ahmetvaleev.

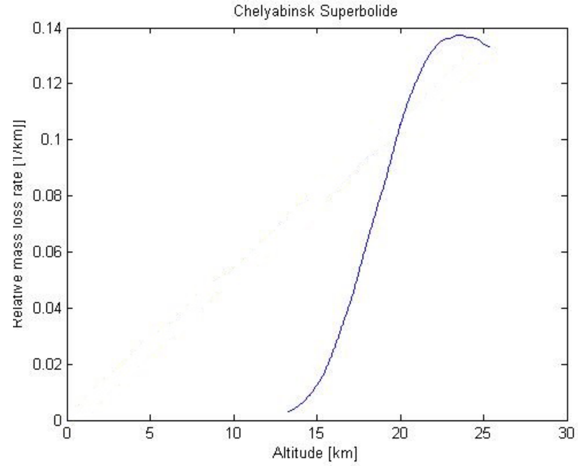

Figure 3: Relative mass loss rate as a function of height over the sea level.

3. Summary and Conclusions

So far we have obtained very promising results on the dynamic behavior of Chelyabinsk superbolide in the lower part of its atmospheric trajectory. Our Runge Kutta model predict nicely the main observed characteristics of this superbolide, and provides an averaged ablation coefficient $\sigma=0.034$ s^2 km^{-2}.

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