A preliminary reconstruction of the orbit of the Chelyabinsk Meteoroid

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Abstract

In February 15 2013 a medium-sized meteoroid impacted the atmosphere in the region of Chelyabinsk, Russia. After its entrance to the atmosphere and after travel by several hundred of kilometers the body exploded in a powerful event responsible for physical damages and injured people spread over a region enclosing several large cities. We present in this letter the results of a preliminary reconstruction of the orbit of the *Chelyabinsk meteoroid*. Using evidence gathered by one camera at the Revolution Square in the city of Chelyabinsk and other videos recorded by witnesses in the close city of Korkino, we calculate the trajectory of the body in the atmosphere and use it to reconstruct the orbit in space of the meteoroid previous to the violent encounter with our planet. In order to account for the uncertainties implicit in the determination of the trajectory of the body in the atmosphere, we use Monte Carlo methods to calculate the most probable orbital parameters and their dispersion. Although the orbital elements are affected by uncertainties the orbit has been sucesfully reconstructed. We use it to classify the meteoroid among the near Earth asteroid families finding that the parent body belonged to the Apollo asteroids.

Keywords: Meteors, Asteroid, dynamics

1. Introduction

In February 15 2013 at about 09:20 local time a large fireball followed by a huge explosion was seen in the skies of the Chelyabinsk region in Russia. Cameras all across the region registered the historic event creating an ah-hoc network of instruments able to potentially provide enough visual information for a reconstruction of the trajectory of the body in the atmosphere and from it the orbit of the meteoroid.

The ballistic reconstruction of the orbit of bodies associated to bright fireballs is one of the tools used to study the nature and origin of these bodies. There are a relatively small number of bright-bolides whose orbit has been successfully reconstructed, even despite the

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relatively large number of cases reported every year (see e.g. Trigo-Rodríguez *et al.* 2009). In some cases the lack of enough number of observations or a limited quality in the available observations renders impossible the reconstruction of the orbit.

In the case of the Chelyabinsk meteoroid the number of observations and the quality of some of them seem to be enough for a successful reconstruction of the meteoroid orbit. More than several tens of videos, ranging from amateur videos, videos recorded by onboard vehicle cameras and cameras of the public transit and police network are readily available in the web (for a large although incomplete compilation of videos see http://goo.gl/rbdZm¹)

In this letter we present one of the first rigorous attempts to reconstruct the orbit of the Chelyabinsk Meteoroid. We use here the recording of a camera located in the Revolutionary Square in Chelyabinsk and one video recorded in the close city of Korkino. Both observations are used to triangulate the trajectory of the body in the atmosphere. The method used is here was first devised by Stefen Geen and published in one his blog, *Ogle Earth* http://goo.gl/vcG3Y in February 16 2013.

Further details, updates, videos and additional images and plots that those released on this letter are available at http://astronomia.udea.edu.co/chelyabinsk-meteoroid.

Although an analysis of the data taken by scientific instruments in the affected area, combined with further analyses of the abundant information gathered by eye witnesses and in situ cameras, would allow a precise determination of the meteoroid orbit, a first attempt to reconstruct the orbit of the meteoroid would help us to ellucidate its nature and origin and would certainly improve the on-going research on the event.

2. Trajectory in the atmosphere

To reconstruct the trajectory in the atmosphere we use the same method and images originally used by Stefan Geen and publickly available in his blog *Ogle Earth*. The original blog entry is available here http://goo.gl/vcG3Y. It is interesting to stress that at using the methods and results published in the Geen's blog, we are recognizing the fundamental contribution that enthusiastic people would have in specific scientific achievements. Similar cases of interaction between active enthusiastic contributors (a.k.a. *citizen astronomers*) and professionals have been recently seen in other areas in astronomy (see e.g. Lintott *et al.* 2008 and Fischer *et al.* 2012)

The method cleverly devised by Geen uses the shadow cast by light poles at the Revolution Square of Chelyabinsk during the flyby of the fireball, to estimate the elevation and azimuth of the meteoroid at different stages if its impact with the atmosphere (the original video can be found at http://goo.gl/nNcvq). To calculate elevations he height of the light poles is estimated by comparing them with their separation as given by Google Earth images and tools. Azimuts are calculated from the angle subtended by the shadows and the border of the Prospect Lenina street in front of the square. The street and the square are almost perfectly aligned with the East-West and South-North directions.

¹Hereafter and to save space we will shorten all urls.

For our reconstruction of the trajectory we have selected two particular times in the images recorded by a public camera located in front of the square. The first one correspond to the point when the fireball reaches a brightness enough to give clear shadows of the poles. We call this point the "brightening point" (BP). A local elevation $a_{\rm BP}=33^o$ and an azimut $A_{\rm EP}=122^o$ were found after analysing the corresponding video frame. The second time coincides approximately with the closest point of the trajectory to the observing point. It also coincides with the time where the bolid starts to fragmentate. We call this second reference point the "fragmentation point" (FP). The FP elevation and azimut are measured as $h_{\rm FP}=32^o$ and $A_{\rm EP}=222^o$. The time required by the meteoroid to travel between those two points is estimated from the time stamps in the video and it was found equal to $\Delta t=3.5$ s. We assume that the local time of the meteoroid passage by BP is precisely provided by the time stamps in the video. Hereafter we will assume $t_{\rm BP}=9~h~20~m~29~s$. This time could be affected by uncertainties up to few seconds.

The information provided by a single observer is not enough to determine the meteoroid trajectory in the atmosphere. In particular we need an independent observation to estimate for example the distance and height of BP and FP with respect to the Revolution Square. There are several tens of independent and publickly available videos shoot at very different points in a radius of almost 700 km. However most of them were recorded by amateur equipment or cameras in vehicles making complicated to find a suitable parable of the "virtual observations" performed at Revolution Square. At the time of writing of this letter no video was yet identified with the required information to triangulate in a precise way the meteoroid trajectory.

There is an extraordinary coincidence that help us to constraint the distance of the meteoroid to the center of Cheliabinsk. Eye witnesses and videos show that at Korkin a small city to the south of Chelyabinsk, the fireball streak across the local zenith. In the video publickly available here http://goo.gl/OHhDR it can be seen how the meteoroid was moving close to the zenith when the body exploded above the place were the video was shot. The precise location of the recording camera has not been yet reported by the author. Other observers at Korkino registered in video the huge contrail left by the meteoroid. Their observations confirm that the fireball passed almost through the first vertical. In those cases again no precise information of the geographic location of the camara was either provided by the authors.

Finally a third vantage point should be selected to complete the triangulation of the meteoroid. As originally suggested by Stefan Geen the third point was chosen to be the surface of Lake Chebarkul, one of the many lakes in the Chelyabinsk region and so far the only place where a large hole in the ice were preliminarly associated with the impact of a large fragment of the meteoroid. Assuming that the fragment traveled in the same direction that the meteoroid in the atmosphere, Lake Chebarkul provie the intersection of the meteoroid trajaectory with the Earth surface.

Combining the information provided by the shadows at the center of Chelyabinsk, the videos and observations of the fireball and its contrail at Gorkin and the impact at lake Chebarkul, the trajectory of the meteoroid in the atmosphere can be constrained to the region depicted in Figure 1.

There are six critical properties describing the trajectory in the atmosphere and that we need to estimate in order to proceed at reconstructing the orbit in space. The linear height H of the reference point BP; the elevation a and azimuth A of the meteor radiant which is the same elevation and aizmut of the trajectory as seen from the impact point; the latitude ϕ , and longitude λ of the surface point right below BP, and the velocity v of the meteoroid at SP that we will assume equal to its orbital velocity.

All these properties are function of a single unknown free parameter: the distance d between the central square at Chelyabinsk(C) and the surface point below BP (see right panel in figure 1. Each value of d correspond to a value of the azimut of the trajectory compatible with the fact that the fireball streaks the sky close or at the zenith at some points in Korkino. The latter condition implies that d is between 50 and 72 km.

In table 1 we present the properties of the trajectories defined by the extreme values of the independent parameter d.

Property	Symbol	d = 50 km	d = 72 km	Units
Height at BP	H_{BP}	32.47	46.75	km
Elevation BP	h	16.32	19.73	degree
Azimut BP	A	91.60	96.48	degree
Latitude below BP	ϕ	54.92	54.81	degree
Longitude below BP	λ	62.06	62.35	degree
Height at FP	$H_{ m FP}$	20.31	25.04	km
Radiant declination	δ	12.38	12.39	degree
Radiant right ascension	RA	22.44	22.07	hour
Meteoroid velocity	v	13.43	19.65	$\mathrm{km/s}$

Table 1: Properties of the trajectory for two extreme values of the horizontal distance d between the Revolutionary Square at Chelyabinsk and the meteoroid brightening point (BP). The equatorial coordinates of the radiant δ and RA were calculated assuming that the meteoroid was at BP at 9 h 20 m 29 s. Heights and velocity are measured with respect to the surface of the Earth.

According to our estimations, the Chelyabinski meteor started to brighten up when it was between 32 and 47 km up in the atmosphere. The radiant of the meteoroid was located in the constellation of Pegasus (northern hemisphere). At the time of the event the radiant was close to the East horizon where the sun was starting to rise (this is confirmed by many videos showing the first appearance of the meteor during the twilight, see an example at). The velocity of the body predicted by our analysis was between 13 and 19 km/s (relative to the Earth) which encloses the preferred figure of 18 km/s assumed by other researchers. The relatively large range of velocities compatible with our uncertainties in the direction of the trajectory, represent the largest source of dispersion in the reconstruction of the orbit.

3. Orbit reconstruction

Once the basic properties of the trajectory in the atmosphere have been estimated we need to select a position of the body in the trajectory and express it with respect to a local

reference frame. The selected position will be the initial point of our reconstructed orbit.

The position of the initial point is expressed first in spherical coordinates (latitude, longitude and height with respect to the geoid). We need to transform it first to the International Terrestrial Reference System (ITRS) expressing it in cartesian coordinates. Then the position should be transformed to the Geocentric Celestial Reference System (GCRS) in order to account for the rotation of the Earth. Finally and before we proceed with the integration, we need to rotate the position to a planetocentric ecliptic coordinate system.

We perform all these tasks using NOVAS, the Naval Observatory Vector Astrometry Software developed and distributed by the U.S. Navy Observatory (USNO) (Bangert *et al.* 2011)². In all cases we have checked that the numbers returned in the transformation procedures are in agreement with what should be expected.

In order to integrate the orbit we construct a gravitational scenario including the 8 major solar system planets plus the Earth's Moon. We compute the exact position of these bodies at the precise time of the impact using the JPL DE421 ephemeris kernel and the NAIF/SPICE toolkit (Acton Jr 1996) 3

To integrate the orbit we use Mercury (Chambers 2008). Mercury allows us to integrate backwards the trajectory of the meteoroid taking into account potential perturbing close encounters with the Earth, Moon or Mars. In all cases the orbit of the meteoroid was integrated backwards, 4 years before the impact.

In order to account for the uncertainties in the trajectory we integrate the orbit of 50 different bodies having initial point BP with properties compatible with the uncertainties described before. To perform this integration we generated 50 random values of the distance d uniformly distributed between 50 and 72 km. The rest of properties of the trajectory in the atmosphere were calculated for each value of d. In all cases the trajectories of the bodies were integrated in the same gravitational scenario and using the same parameters of the numerical integrator.

As a result of our Monte Carlo approach, a set of 50 different reconstructed orbits were obtained. The statistical properties of the sample are presented in table 2.

Property	Symbol (units)	Min.	Max.	Median	Mean \pm St.Dev.
Semimajor axis	a (AU)	1.40	2.21	1.69	1.73 ± 0.23
Eccentricity	e	0.37	0.65	0.51	0.51 ± 0.08
Inclination	$i (^{o})$	0.03	6.98	3.30	3.45 ± 2.02
Argument of periapsis	ω (°)	116.06	125.25	120.75	120.62 ± 2.77
Longitude of ascending node	Ω (°)	326.50	331.87	326.51	326.70 ± 0.79
Perihelion distance	q (AU)	0.77	0.88	0.82	0.82 ± 0.03
Aphelion distance	Q(AU)	1.93	3.64	2.55	$\boldsymbol{2.64\pm0.49}$

Table 2: Orbital elements statistics calculated for the Monte Carlo sample drawn in this work to reconstruct the orbit of the Chelyabinsk meteoroid.

²The package and its documentation can be download from http://goo.gl/58kLt

³URL: http://naif.jpl.nasa.gov/naif/toolkit.html.

As expected, a large uncertainty in the impact velocity leads to large uncertainties in the orbital elements. The most affected is the semimajor axis. Orbits with a as large as 2.2 AU and as small as 1.4 AU were found varying the parameters of the meteoroid trajectory in the atmosphere. Despite the uncertainties, several bulk characteristics of the orbit can be reliably established. Eccentricity and perihelion distance are determined at a level of around 10% error or less. The inclination, although still uncertain is in the order of magnitude of what we would expect. Longitude of the asscending node and argument of the periapsis are essentially determined by the point in the meteoroid orbit where it intersects the Earth's orbit. Since all the orbits satisfy the condition to be in the same position at the same date (the impact date) these two elements are essentially the same across the whole sample.

To illustrate graphically this results we show in Figure 3 the reconstructed orbit and two extreme orbits compatible with the uncertainties of our reconstruction. We see in that although we cannot individualize a given orbit, the general features of the meteoroid trajectory were reconstructed successfully with our procedure.

Finally we want to classify the meteoroid by comparing its orbit with that of already known asteroidal families. To achieve this goal we have plotted in an a-e diagram the orbital elements in the random sample and compare them with that of already known Asteroids belonging to the Apollo, Amor and Atens families. The results is depicted in Figure 2. We can better appreciate here the large uncertainties in semimajor axis arising from this type of reconstruction procedure. According to this Figure the Chelyabinsk meteoroid belonged inequivocally to the Apollo family of Asteroids.

4. Discussion and Conclusions

We have reconstructed the orbit of the Chelyabinsk meteoroid. We used the most reliable information that can be found in the increasing amount of evidence recorded in video in the affected area. This is not the first attempt at reconstructing the orbit of this important object and will not be the final one. However it is the most rigurous reconstruction based solely in the evidence gathered in situ by amateur and public cameras.

There are several important assumptions and hypothesis supporting our results. In the first place we assume that the time stamps used by the camera at the Revolution Square in Cheliabinsk are precise. Being a public camera recorder it is expected that some care is put at maintaining the clock of the camera on time. This is not precisely the case in most of the rest of videos available in the web where camera clocks display times off by seconds to minutes with respect to the time of the event. We have verified by running a small Monte Carlo sample of 10 orbits that the statistical conclusions presented here are not affected when the initial time is shifted up to 5 seconds with respect to that shown in the camera log.

The largest source of uncertainty in our reconstruction, is the qualitative nature of the observational evidence in the second vantage point used in the "triangulation" of the meteoroid trajectory. Although every video filmed at Korkin shows that the fireball crossed the small city skies almost vertically there are not quantitative evidence supporting this or allowing us quantifying how "vertical" the phenomenon actually. Further efforts to clarify

this point should be attempted to reduce the uncertainties in the direction and velocity of the reconstructed trajectory.

Assuming that the hole in the ice sheet of Lake Cherbakul was produced by a fragment of the meteoroid is also a very important hypothesis of this work. More importantly, our conclusions relies strongly onto assume that the direction of the trajectory of the fragment responsible for the breaking of the ice sheet in the Lake, is essentially the same as the direction of the parent body. It could be not the case. After the explosion and fragmentation of the meteoroid fragments could acquire different velocities and fall affecting areas far from the region wher we expect to find.

Our estimation of the meteoroid orbital velocity assume that this quantity is constant during the penetration in the atmosphere. Although velocities larger than 10 km/s should not be modified too much before the meteoroid explosion or break up the points of the trajectory used in our reconstruction were close to time of explosion and fragmentation of the meteoroid. Accordingly we would expect that our estimations of the velocity will underestimates the orbital velocity outside the atmosphee. A consequence of this would be that the size of the actual orbit could be larger than that obtained here.

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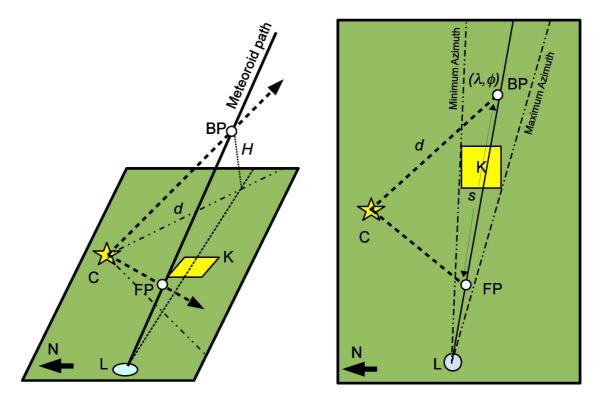


Figure 1: Schematic representation of the trajectory of the meteoroid with respect to three vantages points used here to triangulate the meteoroid trajectory: the Revolution Square at Chelyabinsk (C), the Korkin metropolitan area (K) and Lake Chebarkul (L). The brightening point (BP) and the fragmentation point (FP) are the points of the trajectory seen from Chelyabinsk and measured using the shadow cast by the poles at the Revolutionary Square. Observations at K constraint the azimuth of the trajectory (solid line in the right panel) to be between a minimum and a maximum azimuth. At a given azimuth the distance d between C and the surface point below BP, the height H of BP, and the distance s traveled by the meteoroid between BP and FP, can be calculated. The latitude (ϕ) and longitude (λ) of the BP were assumed as the planetocentric spherical coordinates of the initial point of the reconstructed orbit of the meteoroid.

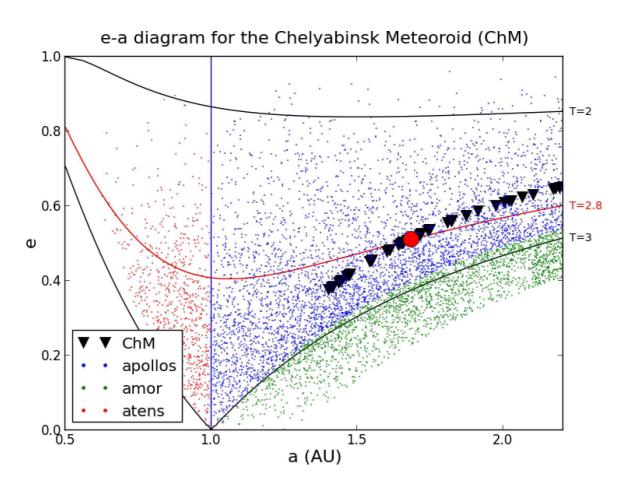


Figure 2: Orbital elements of the reconstructed orbits in the Monte Carlo sample (black triangles). The red circle is close to the median values of a and e. For comparison we included the orbital parameters of the Apollo asteroids (blue dots), Amor asteroids (green dots) and the Atens asteroids (red dots). Curves of equal values of the Tisserand parameter relative to Earth, $T = a_E/a + 2\sqrt{a/a_E(1-e^2)}\cos i$ were also included for reference purposes.

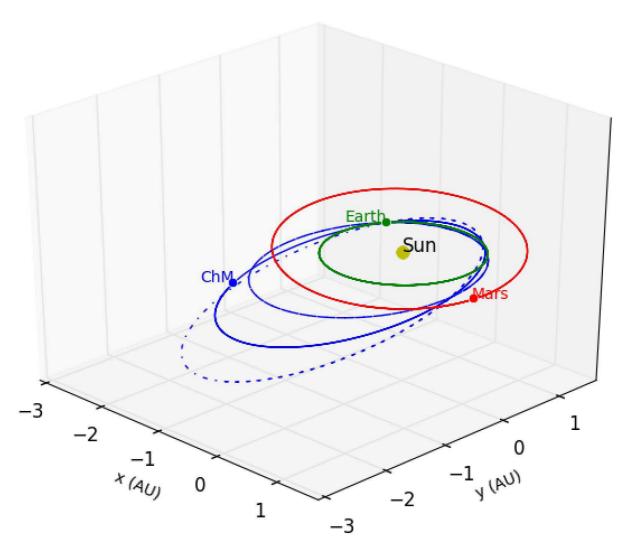


Figure 3: Reconstructed orbits for the Chelyabinsk meteoroid. For reference the orbits of Earth and Mars are represented. The rest of inner and outer planets though not shown were taken into account in the integration of the meteoroid orbit. The meteoroid orbit with the continuous line shows the orbit whose properties are closer to the median orbit, i.e. half of the orbits found in the Monte Carlo are bigger, more eccentric, and more inclined than this. The dot-dashed and dashed orbits correspond to orbits 1-sigma to the left and to the right of the median orbit.