Can we predict the impact conditions of metre-sized meteoroids?

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Abstract

Every year, a few metre-sized meteoroids impact the atmosphere of the Earth. Most (if not all) of them are undetectable before the impact. Therefore, predicting where and how they will fall seems to be an impossible task. In this letter, we show compelling evidence that we can constrain in advance, the dynamical and geometrical conditions of an impact. For this purpose, we analyse the well-documented case of the Chelyabinsk (Russia) impact and the more recent and smaller Viñales (Cuba) event, whose conditions we estimate and provide here. After using the Gravitational Ray Tracing (GRT) algorithm to ‘predict’ the impact conditions of the aforementioned events, we find that the speed, incoming direction, and (marginally) the orbital elements of the corresponding meteoroids could be constrained in advance, starting on only one hand, with the geographical location and time of the impact, and on the other hand, with the distribution in configuration space of near-Earth objects (NEOs). Any improvement in our capability to predict or at least to constrain impact properties of medium-sized and large meteoroids will help us to be better prepared for its potentially damaging effects.

Key words: methods: numerical – meteorites, meteors, meteoroids.

1 INTRODUCTION

Earth is impacted by hundreds to thousands of centimetre-sized meteoroids each year. Metre-sized objects are much less frequent, with just a few of them falling into the Earth every year (Brown et al. 2013). Most of these events occur at very high altitudes and far from populated areas. Still, they are detectable by satellites (Chapman & Morrison 1994; Brown et al. 2002) and infrasound detectors (see e.g. Silber, Le Pichon & Brown 2011; Moreno-Ibáñez et al. 2018). In a few cases, however, an impact of a metre-sized object (releasing energies in the range of few to several to hundreds of ktons) may happen over populated areas, posing a real risk over infrastructure and population (Popova et al. 2013; Rumpf, Lewis & Atkinson 2016).

In the case of large (several hundreds of meters) and well-known near-Earth objects (NEOs) whose impact probabilities are not negligible, we can predict in advance where and how the object could impact our planet (Chapman 2004; Chesley 2005; Rumpf et al. 2016). This is possible because the impactor has been previously observed and its orbital elements are very well constrained.

The detection of metre-sized NEOs is slow and difficult (see e.g. Boslough, Brown & Harris 2015). Therefore, predicting where and how one of these unseen objects will impact our planet at a given time seems to be an impossible task. Proof of this is the well-known impacts in Chelyabinsk (Russia), Benenitra (Madagascar) and recently in Viñales (Cuba) and the Bering Sea, (Russia), which were not observed prior to the event.

In two recent works, Zuluaga & Sucerquia (2017, 2018) introduced a novel numerical technique, the Gravitational Ray Tracing (GRT), intended (among many potential applications) to compute the probability that at a given time, certain geographical region of the Earth (or any other planetary body) be impacted by a meteoroid. More recently Zuluaga et al. (2019) applied GRT to study the impact of a small object against the moon, testing the technique for the first time in a different context and with a different aim for which it was originally devised.

In this Letter, we apply GRT (Section 4) to study retrospectively the impact conditions (Section 2) of the best documented atmospheric explosion to date, namely the Chelyabinsk impact, hereafter the Chelyabinsk-Russia or C-R event (Section 3), and the more recent, smaller, but still energetic event over Viñales (Cuba), hereafter the Viñales-Cuba or V-C event. Our aim here is to verify if the ‘predictions’ that GRT could make about the incoming direction, speed and orbital element of the potential impactors at the place and time of those events (Section 5), are close to the observed conditions of the impacts. In order to perform the comparison between the well-known C-R event with the barely studied V-C impact, we provide our own estimations of the impact conditions as obtained from public footage and using the methods introduced in Zuluaga, Ferrin & Geens (2013, Supplementary material).
2 IMPACT CONDITIONS

After encountering the Earth, the fate of a meteoroid depends on many different parameters, including its pre-entry size, mass, and incoming direction (Gritsevich, Stulov & Turchak 2012; Lytten & Gritsevich 2016). Still, most (if not all) metre-sized objects, i.e. diameters $1 \lesssim D \lesssim 50$ m, which have impacted the Earth in the last 30 yr leaving a detectable fireball, have exploded at altitudes ranging $20–50$ km, in accordance with most theoretical expectations (Svetsov, Nemtchinov & Teterov 1995; Collins, Melosh & Marcus 2005). Ablation and subsequent fragmentation happen when the atmospheric density increases and the aerodynamic pressure at the leading edge of the impactor surpasses the strength of the material (Hills & Goda 1998). Usually, the ‘cascade’ breakup of the main body spreads material of the meteoroid over a relatively large area of the planet surface.

We call ‘impact conditions’ to the set of bulk geometrical and dynamical properties of a meteoroid impact on the Earth’s atmosphere. These conditions include but are not restricted to the entry speed, incoming direction, and projected impact point.

We call projected impact point to the intersection between the geoid and a straight line tangent to the atmospheric trajectory of the meteoroid. Their geodetic coordinates are denoted as $\text{lon}_\text{imp}, \text{lat}_\text{imp}$. The point in the sky from which the meteoroid seems to come is known as the radiant. Here, we parametrize the radiant in terms of the Azimuth ($\lambda_{\text{rad}}$) and elevation ($\varphi_{\text{rad}}$) of this direction as observed from the projected impact point.

Since the impact speed $v_{\text{imp}}$ of the meteoroid is relatively large, typically $v_{\text{imp}} \sim 12–24$ km s$^{-1}$, and its mass is much larger than the mass of the atmosphere displaced during the ablation, the trajectory of the meteor can be assumed nearly rectilinear until it reaches the upper layers of the lower atmosphere, i.e. altitudes $\sim 20–30$ km. Therefore, after determining the projected impact point and the radiant direction we can estimate the heliocentric orbital elements prior to impact, namely $q$, $e$, $i$, $\Omega$, and $\omega$ (with $q$ the perihelion distance, $e$ the eccentricity, $i$ the orbital inclination, $\Omega$ the longitude of ascending node, and $\omega$ the argument of perihelion). These elements are obtained by integrating the trajectory of the object, subject to the gravitational field of the Solar system, back to a reasonable time previous to impact (typically one orbital period before).

3 STUDIED EVENTS

In recent years, the expansion and densification of urban areas plus the availability of cheap electronic cameras, allowed that two large impact events be witnessed and registered by thousands to millions of casual observers. The first one was the Chelyabinsk-Russia (C-R) event (2013 February 15), the largest reported fireball since the Tunguska-Russia impact. More recently a smaller, still energetic, impact was witnessed in Viñales, Cuba (2019 February 1), the V-C event. Other relatively large events, such as one in Madagascar (2018 July 27), had also thousands of witnesses, but much less available footage and data. Multiple sources of information, including public footage, satellite imagery and recordings from infrasound networks, has allowed us to determine with incredible detail (at least in the case of C-R impact) the impact conditions of these two events.

We provide in the supplementary material, full details of a detailed estimation of the V-C event impact conditions, as obtained exclusively from public footage, and applying the methods previously introduced in Zuluaga et al. (2013). In Table 1, we show the impact conditions for the C-R and V-C events, as obtained from the available literature (Borovička et al. 2013; Popova et al. 2013; Zuluaga et al. 2013) and according to our own estimations.

4 GRAVITATIONAL RAY TRACING

Are the impact of meteoroids and their specific conditions predictable? As stated above, the small size of most of the objects falling into the Earth each year, prevents their early detection, making very improbable, if not entirely impossible, to anticipate their place and conditions of arrival.

Zuluaga &Sucerquia (2017, 2018, hereafter ZS2018) developed and tested a backward integration technique intended to compute the statistical properties of these impacts. The technique was inspired in the ray tracing algorithms used in the film and game industries to render photorealistic images (see e.g. Comninos 2010 and references therein), which also inspired the name of the technique, GRT.

In GRT, we randomly generate $N$ different impact velocities regularly spaced in the interval $11.1–43.6$ km s$^{-1}$ (the Earth’s escape velocity and the biggest possible velocity achievable at Earth’s orbit, respectively, see ZS2018 for details) and $M$ random incoming directions following a blue-noise distribution to avoid aliasing sampling effects (see section 2.1 in ZS2018). Starting at a given impact site and a desired date and time, we integrate backwards the trajectory of these $N \times M$ test particles in the Solar system gravitational field. The integration stops when test particles reach an asymptotic heliocentric orbit.

The probability that a test particle, having impact conditions ($A$, $v_{\text{imp}}$), correspond to a real meteoroid, is given by the so-called ray probability:

$$P(A, v_{\text{imp}}; t) \propto f(\theta_{\text{apex}}, \lambda_{\text{apex}})R(q, e, i, \Omega, \omega).$$

Here, $R(q, e, i, \Omega, \omega)$ is the number density of NEOs in the orbital elements space (see Section 6 for a discussion). In order to correct

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**Table 1.** Impact conditions of the impact events studied in this work.

| Property                  | C-R$^a$ (2013) | V-C$^b$ (2019) |
|---------------------------|----------------|----------------|
| Date                      | Borovička et al. (2013) | This work |
| Time (UTC)                | 2013/02/15     | 2018/02/01     |
| $v_{\text{imp}}$ (km s$^{-1}$) | 107.67 18.55   | 103.5 18.55    |
| $\text{lon}_\text{imp}$ (deg) | +59.8703+55.0958e | +326.459 326.459 |
| $\text{lat}_\text{imp}$ (deg) | +107.67 18.55  | +107.67 18.55  |

$^a$C-R, Chelyabinsk-Russia; $^b$V-C, Viñales-Cuba; $^c$Zuluaga et al. (2013); $^d$Tisserand parameter, $T_p = 1/a + 2 \cos i \sqrt{a(1-e^2)}$. 

For an updated list of reported fireballs in the CNEOS database see: [http://cneos.jpl.nasa.gov/football/](http://cneos.jpl.nasa.gov/football/) (Manager Paul Chodas, Designers Shakeh Khadikhyan, Alan Chamberlain).
for the ‘defocusing’ effect that the relative motion of the Earth has with respect to the NEOs population, we introduce a flux correcting factor \( f \) (see section 2.5 in ZS2018):

\[
f(u = \cos(90 - \theta_{\text{apex}}); a, b) = \begin{cases} 
  u^a - 1 & \text{if } u < 0; \\
  u^b & \text{if } 0 \leq u \leq 1.
\end{cases}
\] (1)

where \( \theta_{\text{apex}} \) and \( \lambda_{\text{apex}} \) are the polar and azimuthal angle of the incoming direction with respect to the apex (direction of motion of the Earth). \( a \approx 1 \) and \( b \approx 0.5 \) are constants that we fit using the frequency as a function of apex angle of meteors in the CNEOS fireball reports database. The number density of NEOs around a point \( x = (q, e, i, \Omega, \omega) \) in configuration space is estimated with

\[
R(x) = \sum_k W(||x - x_i||, \eta),
\] (2)

where \( ||x - x_i|| \) is a generalized ‘distance’ and \( \eta \) a scale parameter. \( W(||x - x_i||, \eta) \) is called the smoothing kernel, and it is intended to soft the transition from a discrete to a continuous regime (see equation 7 in ZS2018). The sum in \( R \) include all the NEOs \( k \) at a distance less than \( 2\eta \) of the point \( x \).

Distances in configuration space \( ||x - x_i|| \) are computed using the Zappala et al. (1990) metric with the parametrization introduced by Roerrozdotzek, Breiter & Jopek (2011):

\[
(D_x/n_m a_m)^2 = \frac{5}{4} (a - a_m)^2/a_m^2 + 2(e - e_k)^2 + 2\sin^2 i \sin^2 i_k \left( 1 - \frac{1}{2} e_k^2 \right) + \left( 1 - \frac{1}{2} e_k^2 \right)^3 (\Omega - \Omega_k)^2 + \left( 1 - \frac{1}{2} e_k^2 \right)^2 (\omega - \omega_k)^2
\] (3)

with \( a_m = (a + a_k)/2 \) the average semimajor axis between, \( n_m \) the corresponding orbital mean motion, and \( \sigma = \Omega + \omega \) the longitude of the perihelion.

### 4.1 Marginal probabilities

In ZS2018, we sum up the ray probabilities at a given geographical location, to compute the (relative) probability that an object hit that location instead of another one. This allows us to create impact risk maps. But ray probabilities can be used in different ways. Thus, for instance, we can estimate the marginal probability distribution of impact speeds, i.e. \( p(v_{\text{imp}}) \), if we sum up the probabilities for all rays having impact speeds in the interval \( V : [v_{\text{imp}}, v_{\text{imp}} + \Delta v_{\text{imp}}] \):

\[
p(v_{\text{imp}}) \Delta v_{\text{imp}} \propto \sum_V P(A_i, h_i, v_{\text{imp}}, t).
\]

The same rationale can be applied for computing the marginal probability distribution of any impact condition (radiant elevation, radiant azimuth, asymptotic orbit semimajor axis, etc.).

In Fig. 1, we show the marginal probability distributions for several quantities, as computed with GRT at the location and time of the C-R and V-C events. A comparison with the true impact conditions is also shown.

A similar approach can be used to compute bivariate marginal probability distributions. Thus, for instance, the probability that the radiant elevation and Azimuth be in the solid angle \( \Delta \Omega \): \( [h_{\text{rad}}, h_{\text{rad}} + \Delta h_{\text{rad}}], [A_{\text{rad}}, A_{\text{rad}} + \Delta A_{\text{rad}}] \) can be estimated by

\[
p(A_{\text{rad}}, h_{\text{rad}}) \propto \sum_{\Delta \Omega} P(A_i, h_i, v_{\text{imp}}, t).
\]

It should be noticed that in this case a geometrical correcting factor, namely \( \cos h_{\text{rad}} \), should be introduced to estimate the probability distribution function, since solid angles at larger elevations are smaller than those near to the horizon.

### 5 RESULTS

Impact conditions (Fig. 1), for both the C-R and V-C events, are well within the statistical errors of the GRT predictions. The case of azimuth is especially interesting. Although the observed value of this quantity, have low marginal probability in both events, GRT predicts correctly the octant in the sky from which the impactors arrived. In the case of C-R event, GRT predicted a north-east radiant, \( A_{\text{rad}} \approx 50°-70° \). In the real impact, the object appeared coming from the east, \( A_{\text{rad}} \approx 100° \). More interesting is the case of the V-C meteoroid. Public observations reported to the American Meteor Society, AMS,\(^2\) as well as early interpretation of the available footage, suggested a southbound meteor direction. The theoretical predictions with GRT (see rightmost panel in the lower row of Fig. 1) predicted that meteoroid should enter travelling from south to north (radiant in the south, \( A_{\text{rad}} \approx 140°-160° \)), as was later confirmed by an independent analysis of satellite images.

In Fig. 2, we show contour maps of the bivariate marginal probability distribution of azimuth and elevation. These maps reveal details absent in the univariate marginal distributions of Fig. 1. Thus, for instance, according to CRT at the date, time, and location of the C-R event, almost no objects should come from azimuths between \( 100° \) and \( 270° \) (half of the sky), nor from elevations lower than \( 15° \). The actual meteor arrived from a point in the sky well-inside the predicted region. In the V-C case, the ‘forbidden region’ is smaller and two well-recognized spots at \( A \approx 150°, h \approx 10°-40° \) and \( A \approx 40°, h \approx 50°-60° \) concentrate the expected incoming directions. The actual meteoroid came close to the first spot.

The heliocentric elements of the meteoroids also show interesting coincidences with those predicted by GRT. In Fig. 3, we show bivariate marginal probability distribution for pairs of orbital elements. For the C-R event, GRT favours a low-inclination meteoroid orbit with a moderate \( e \approx 0.4-0.6 \) eccentricity which is close to the actual impactor orbit. For the V-C event, GRT predicted a similar eccentricity but a slightly larger orbital inclination. The actual body had \( i \approx 11° \), \( e \approx 0.4 \). The longitude of the ascending node \( \Omega \) is easy to predict. It will mostly depend on the ecliptic longitude of the Earth at the time of impact. However, the argument of the perihelion \( \omega \), namely the orientation of the axes of the ellipse in the orbital plane, is not trivial to predict. Still, GRT constrains reasonably well the value of \( \omega \) for both events.

### 6 DISCUSSION

We started this Letter by formulating a bold question: can we predict the impact conditions of metre-sized meteoroids? After the results presented in this work, which certainly does not constitute a statistically significant prove, we propose also a bold answer: yes, we can predict them. But this answer should not surprise us. As GRT intrinsically assumes, the NEOs population acts like a gravitational ‘source of light’ that instead of photons sends particles towards the Earth. Predicting the incoming impact direction is a simple consequence of knowing the properties of such body source.

The quality of GRT predictions depends on meteoroid population used for calculation ray probabilities. In this paper and for the sake of simplicity, we assumed that all potential impacting bodies have an orbital distribution similar to that of the complete NEO population (\( \sim 20,000 \) objects with absolute magnitude \( H < 20 \) and diameters

\(^2\)https://fireball.amsmeteors.org/members/imo/view/event/2019/513

(Director David Maisel, Visual Meteor Cordinateur Kim Hay, Developer Vincent Perlerin)
Figure 1. Marginal probability distributions of impact velocity, elevation, and azimuth for C-R (upper row) and V-C (lower row) events.

Figure 2. The estimated radiant for the Chelyabinsk (left-hand panel) and Cuba meteor events (right-hand panel), and the most prone meteoroid radiants in colourmaps according to the GRT technique.

Figure 3. Colourmaps show the regions in the configuration $(a, e, i, \omega, \Omega)$ space more prone to impact the Earth at the time and place of Chelyabinsk (uppermost panels) and Cuban meteors (lowermost panels).
we predict Impact conditions

D > 500 m). However, smaller and fainter objects, which are affected for instance by non-gravitational forces, may have different distributions (see e.g. Granvik et al. 2017) or, as it is the case of centimetre-sized particles, they may have multiple and diverse sources (major meteor showers, sporadic meteor torus). Other assumptions on the distribution of small and invisible impactors may be used to improve GRT following the recent results by Bouquet et al. (2014), Christou et al. (2014), Dmitriev, Lupovka & Gritsevich (2015), and Granvik et al. (2016, 2017).

Why did we focus on metre-sized meteoroids? Three main reasons. First, we can assume in a first approximation (as we have done in ZS2018) that they have a similar origin (and probably a similar distribution) as the population of larger NEOs. Even if this is not the case, performing simulations to study their true distribution is rather feasible. Secondly, most of them are missing and still ‘invisible’ to our surveys. And last but not least, they pose the worst risk to our civilization. Their impact rate is relatively high and the potential damaging effects, though small as compared with hundred-metre-sized objects, may have non-negligible economical impacts.

Is GRT perfect and their predictions entirely reliable? Probably not in its present form. As the differences between the predicted and the observed impact conditions seems to reveal, the method can be still improved, not only with a better knowledge of the meteoroid orbital distribution but also from a theoretical and numerical point of view. However, it is hard for a single group of authors to achieve it.

Being able to constrain impact conditions will not solve all the risks imposed by small undetectable objects. Still, it can help us to be prepared for future events, especially over populated areas. With this work, we also want to call the attention of governmental and no governmental institutions about the interest that theoretical research on impact risk assessment may have, and the potential that novel methods like GRT have at finding answer to what were considered unsolvable questions.

Our results here relied in our own estimations of the V-C impact conditions. Although improved conditions could be obtained combining all available information (satellite data, infrasound recordings, more and better footage, etc.), we are confident that the conclusions of this Letter will not be substantially modified.

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Supplementary data are available at MNRASL online.

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