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On the discovery of dangerous asteroids and single-apparition comets. I

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The paper examines the issues of predicting possible collisions with already known asteroids, as well as with comets during their first flyby. The approach to detecting the two types of events differs significantly. The asteroid collision prediction program is being successfully implemented. The development of a system for detecting dangerous comets is at its earliest stage.

Keywords: Asteroid-comet hazard, impact, near earth object, long-period comet

1 Introduction

The asteroid–comet hazard is a real threat of cosmic origin. Such events are quite rare, but the fall of an asteroid or comet nucleus to the Earth's surface can cause numerous casualties. According to some estimates[1] the number of victims from asteroid impacts (of course averaged over a long period of time) is comparable to the number of victims of air crashes at the present time.

In Russia, dangerous asteroids are objects with a diameter exceeding $d_{\min} = 100$ m, in the USA a slightly different but close value $d_{\min} = 140$ m is used. The fall of such objects causes the formation of a crater with a diameter of 1.5–2 km, like the Arizona crater, and causes the death of living beings, destruction and fires at a distance of several tens of kilometers from the point of impact. However, the consequences of the Tungeska event (30/06/1908) and Chelyabinsk meteorite (15/02/2013), generated by space objects with dimensions of only 20–30 m, indicate the possibility of lowering this level.

More detailed information on various aspects of the asteroid-comet hazard can be found in Trigo-Rodríguez (2022) and Shustov and Prokhorov (2024).

The first and most important step in countering the asteroid threat is to detect the object colliding with Earth, determine its size, the time remaining before impact, and

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[1]It should be noted that these estimates are not very reliable.

the impact location. The approach to detecting the fact of impact differs significantly for already known near-Earth asteroids (which also include short-period comets) and for newly observed long-period comets that will collide with Earth during their first flyby of the Sun after discovery. We will consider these cases, with a particular focus on the second type of object.

2 Collision detection with already known objects

To date, about 1.5 million asteroids (mostly in the Main Asteroid Belt) and about 4,500 comets are known. Most of them pose no danger to the Earth. Of the many small bodies in the solar system, the so-called near-Earth asteroids/objects (NEA or NEO) are distinguished, which approach the Sun at a distance less than $q < 1.3$ au. Of the NEA, the so-called potentially hazardous objects/asteroids (PHO or PHA) are distinguished and for which, in addition to the perihelion distance limitation q, two more conditions are met: 1) these objects approach the Earth's orbit at a distance less than $\Delta R < 7.5 \cdot 10^6$ km (0.05 au); 2) they are large enough to cause serious consequences, with an absolute stellar magnitude of $H < 22^m$ (with an albedo of $A = 0.15$, this value corresponds to a spherical asteroid with a diameter of 140 m). The value of ΔR is the average error (over the entire set of objects) with which the position of asteroids is determined 100 years from the present moment.

Asteroids, including NEA, are being discovered through a number of observational programs. Among them are those entirely focused on asteroid detection (Wikipedia 2017), in others, asteroid prospecting is only one of the goals of the study (Wikipedia 2020).

NEA detection during these surveys is progressing quite well. As of 2025/03/26, 873 NEA with diameter $d > 1$ km, 11249 NEA with $d > 140$ m, and 38045 NEA with no diameter restrictions (CNEOS 2025) have been detected. From the same source it is evident that for NEA with $d > 1$ km the rapid growth in the number of new objects that took place in 2000-2006 is systematically decreasing. Apparently, almost all NEA of these sizes have already been discovered, their total number is unlikely to significantly exceed 1000. At the same time, for NEA with $d > 140$ m there is no such effect, their number is growing linearly with time, therefore, only a small fraction of the population of these asteroids has been discovered to date.

The program for detecting new NEA should be continued, and those already known should be regularly observed and possible future collisions with Earth should be predicted. We will predict collisions tens of years in advance, and later, as the accuracy of NEA orbit prediction increases, hundreds of years in advance. This large time interval will allow us to counteract the collision.

3 Detecting collisions with long-period comets

3.1 Special characteristics of long-period comets

Another class of potentially hazardous bodies are long-period comets (or non-periodic comets). Their periods of revolution around the Sun are $P > 200$ yr. Previous

flights of these comets near the Sun are unknown. Perhaps they are recorded in historical chronicles, but the accuracy of observational data does not allow us to predict the reappearance of these comets. Thus, a new long-period comet can appear at any time and from almost any direction. If the orbits of a comet with periods of $200 < P < 1000$ yr show a concentration toward the ecliptic plane, then for single-apparition comets with $P > 1000$ yr, the distribution of the semimajor axes of the orbits is isotropic (this is one of the arguments in favor of the existence of the Oort cloud). According to the Minor Planet Center (MPC), 384 new long-period comets (∼38 comets per year) have been discovered over the past 10 years (from 2015 to 2024 inclusive). Of these, 65 were NEOs ($q < 1.3$ au), and 50 flew inside the Earth's orbit ($q < 1$ au). The average time interval between the discovery of these 384 comets and their perihelion passage was 1 yr, and the 5% and 95% quantiles are 31 days and 3 yrs[2].

Such comets can be detected, their orbits can be determined, and those that will collide with the Earth can be selected. Moreover, this can be done long enough before the collision for countermeasures. Apparently, the most effective measure of influence is to send a thermonuclear bomb to the comet and explode it there (Pitz et al. 2014). With a ready-made countermeasure system the *minimum* time to influence the comet will probably be 1 month. Such a system does not exist today.

Let us pay attention to two more facts. The sizes of comet nuclei lie in the range from hundreds of meters to 20–30 km. This is a much narrower range than that of asteroids, the largest of which have sizes of ∼500 km in the Main Asteroid Belt and somewhat larger in the Kuiper Belt, and on the small side, asteroids border on meteoroids[3]. The second fact is that according to the results of space missions to comets, the nuclei of many of them have a very low albedo $A = 0.03$–0.04.

Two conclusions follow from the above facts. On one side the small size of comet nuclei means that the impact of thermonuclear bomb on them will be effective, especially if the explosion occurs under the surface of the comet (Pitz et al. 2014). On the other side the small size and low albedo will require fairly large instruments to guarantee the detection of comets a month before the collision. Even larger telescopes will be needed to detect comets a year before impact.

3.2 Problem statement

When detecting dangerous comets, one can try to rely on the data of the same ground-based observatories that search for NEA (Wikipedia 2017, 2020). However, these observatories have very different instruments, their work is not coordinated, therefore, they cannot guarantee the detection of dangerous comets at a given time before the collision with the Earth. In the future, a specialized near-Earth spacecraft (SC) or a small SC constellation should be used to search for dangerous comets. Until such a constellation is launched, ground-based data will be used as a temporary replacement, and after its creation, as a supplement to orbital observations. Below, we will consider observations carried out from aboard a near-Earth spacecraft or constellation.

[2]The estimates were obtained by the authors of this article.

[3]The boundary between asteroids and meteoroids is not clearly defined (Millman 1961). Different authors draw the boundary between these types of objects at diameters from 1 to 100 m (Borovička 2015).

In order to solve the problem of detecting dangerous comets, it is necessary to set two of its parameters: 1) how much time ΔT before the collision should comets be detected; 2) what minimum diameter d objects must be guaranteed to be detected during the time ΔT before the collision. Since the apparent stellar magnitude of the comet's nucleus, in addition to its diameter d, also depends on the albedo of the surface A, it is better to use the absolute stellar magnitude of the comet H, which is an observed combination of d and A, instead of the second parameter.

Long-period comets near the Sun move in orbits with eccentricities close to unity[4]. The comets moving along parabolic trajectories ($e = 1$) have the maximum speed of movement and, accordingly, the maximum distance. We will consider them to determine the control surface where comets are located that will collide with the Earth after a time interval of ΔT.

Let us introduce an inertial coordinate system whose origin is at the center of the Sun, the X axis passes through the collision point, the Y axis lies in the ecliptic plane, and the Z axis is perpendicular to it. The unit of scale is 1 au. The Earth's orbit in this coordinate system is a unit circle in the X–Y plane, and the collision point has coordinates (1,0,0). Let us draw from this point a family of parabolic trajectories along which comets move, differing in direction at the moment of collision. On each of them we put aside a point that corresponds to the moment ΔT before the collision. The set of these points forms a control surface.

Depending on the value of ΔT, the control surface has a different appearance.

1) At small times, for example $\Delta T = 10$ day, the control surface has about spherical shape. At $\Delta T = 20$ day, the control surface is slightly stretched in the direction of the Sun, since the parabolic velocity increases with approach to the Sun. The Earth is inside the control surface, but is shifted relative to its center, since it moves with a circular velocity that is lower than the parabolic velocity (see Fig. 1a).

2) The situation changes when $\Delta T > T_1 = 1/3\sqrt{2}\pi$ yr $\simeq 27.4$ day. T_1 is the time of radial fall with parabolic velocity from a distance of 1 au onto the Sun. At this value of ΔT, the control surface is bifurcated. On the outer one there are comets that collide with the Earth when approaching perihelion, on the inner one – after its passage. The outer and inner control surfaces touch at the point opposite to the collision point. At $\Delta T = T_1$, the Earth is outside the inner control surface, but inside the outer one. As ΔT increases, the radii of the outer and inner control surfaces increase, and their shape again approaches spherical. At $\Delta T \gtrsim 2$ month, the Earth is inside both control surfaces. The situation for $\Delta T = 1$ month $= 30$ day is shown in Fig. 1b.

3) At $\Delta T \simeq 4$ month the radii of the control surfaces are 2–2.5 times greater than the radius of the Earth's orbit. This value of ΔT conventionally marks the boundary between cases 2 and 3. At $\Delta T \gg 1$ yr the radius of the control surface is approximately equal to

$$r_c \simeq (1\,\text{au})\Delta T^{2/3}\,. \tag{1}$$

In this equation ΔT is measured in years. The appearance of the control surfaces for this case is shown in Fig. 1c.

If there are two control surfaces, it is necessary to observe the outer one, since

[4]A comet with a period of $P > 200$ yr and a perihelion of $q < 1.3$ au (which is NEO) will have an eccentricity of $e > 0.96$.

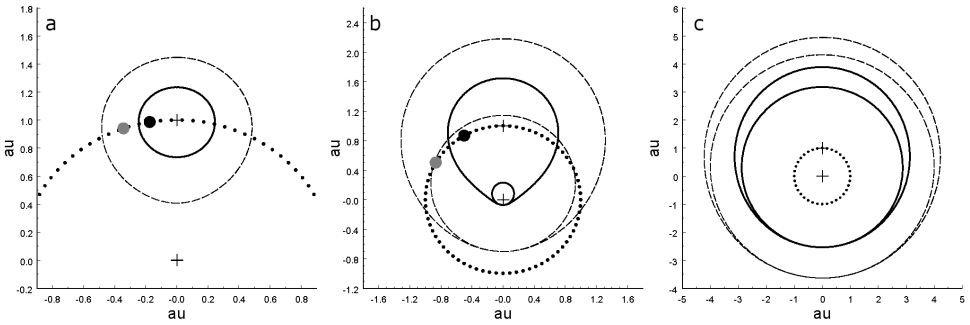


Figure 1 Three possible cases of critical surfaces. Their sections by the ecliptic plane are shown. In all charts, the plus signs indicate the position of the Sun (lower) and the collision point (upper), the dotted line is the Earth's orbit. Chart a is case 1: the solid line shows the critical surface for $\Delta T = 10$ day, the dash line – for $\Delta T = 20$ day, the black circle is the Earth's position for 10 days before the collision, the gray one for 20 days before. Chart b is case 2: the solid line shows the critical surface for $\Delta T = 1$ month, the dash line – for $\Delta T = 2$ month, the black circle is the Earth's position for 1 month before the collision, the gray one for 2 months before. Chart c is case 3: the solid line shows the critical surface for $\Delta T = 6$ months, the dash line – for $\Delta T = 9$ months.

on the inner surface comets of the same size will have a smaller apparent stellar magnitude.

In situations 1 and 3, the phase angles of the comets' illumination are small, which is convenient for their detection. In situation 2, this condition is satisfied for the outer control surface, for the inner one the phase angle varies from 0° to 180° when the Earth is outside of it and within wide limits when the Earth is inside.

The distances from the Earth to different points of the control surfaces vary. In case 1, the ratio of the maximum and minimum distances is approximately described by the formula

$$\frac{r_{\max}}{r_{\min}} \simeq \frac{\sqrt{2}+1}{\sqrt{2}-1} \approx 5.8\,. \tag{2}$$

Without taking into account the difference in phase angles, the maximum difference in the stellar magnitudes of comets visible from Earth on the control surface will be $\sim 3.8^m$.

In case 2, the ratio of the maximum and minimum distances from the Earth to the outer control surface changes in a complex manner depending on ΔT, but remains close to the value from equation (2). In case 3, when $\Delta T > 1$ yr, this relationship is approximately described by the following formula

$$\frac{r_{\max}}{r_{\min}} \simeq \frac{\Delta T^{2/3}+1}{\Delta T^{2/3}-1}\,. \tag{3}$$

As ΔT increases, this ratio decreases to 1, the phase angle tends to 0, and the apparent stellar magnitudes of comets become the same over the entire control surface.

For a comet at any point on the control surface, we know its distances to the Sun and to the Earth, as well as its phase angle. Therefore, knowing its diameter d

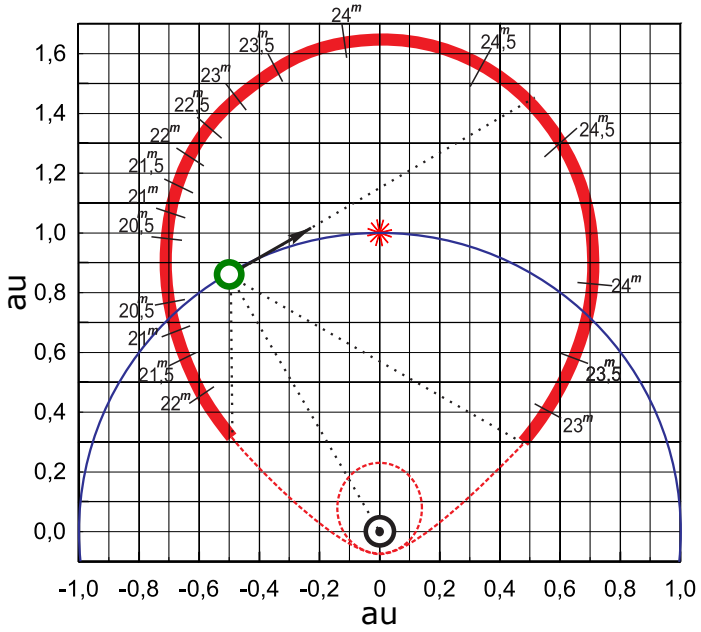


Figure 2 Section of critical surfaces by the ecliptic plane for the case $\Delta T = 30$ day, $d = 100$ m, $A = 0.20$. Symbol $\odot$ indicates the position of the Sun, empty circle – position of the Earth, multi-pointed star – point of collision. Thin solid line – orbit of the Earth, straight arrow – direction of Earth's motion, dotted curve – control surfaces, their part accessible to observations from the Earth is shown by thick solid line, next to which magnitudes of objects visible from the Earth are indicated. Dotted straight lines from the Earth – region 30° around the Sun inaccessible to observations from the Earth. Curves with arrows – some orbits of comets colliding with the Earth.

and albedo A or absolute stellar magnitude H, we can calculate its apparent stellar magnitude. The results of calculations for $\Delta T = 30$ day for an object with $d = 100$ m and $A = 0.20$ are shown in Fig. 2.

For the given parameters, the minimum apparent stellar magnitude of the comet nucleus is $\sim 20.5^m$, and the maximum is $\sim 24.5^m$. The locations of these comets lie at the intersection of the outer control surface with the ecliptic plane in approximately opposite directions from the Earth.

To successfully detect a PHO with given d and A, its signal-to-noise ratio must exceed some minimum level $SNR \geq SNR_{\min} = 5$–10. The signal recorded from a PHO depends on its apparent magnitude, the diameter of the telescope, and the exposure time, while the noise is determined by the background of the starry sky[5]. In the Solar System, the main background of the sky is associated with the zodiacal light (ZL) – solar radiation scattered by interplanetary dust. Far from the plane of the ecliptic ($|\beta| > 30°$) ZL is weak 23.3–23.6^m/sas (sas is an abbreviation of square arc second), where we observe the galactic background. Near the ecliptic, the ZL background is

[5]In addition to the sky background, dark currents and readout noises also contribute to the noise. However, the former can be suppressed by cooling the detector, while the latter are small in modern matrix photosensors.

23.0^m/sas in the antisolar hemisphere and 22.4^m/sas in the solar hemisphere. At an angular distance of $\theta = 45°$ in any direction from the Sun, the ZL background reaches 21.5^m/sas and increases rapidly as we approach the Sun. At $\theta = 30°$, observation of PHO becomes impossible. At approximately the same or slightly larger θ, the telescope is irradiated by the Sun even with a very effective lens hood. We believe that observations of parts of the control surface located at $\theta < 30°$ from a near-Earth spacecraft are impossible.

In situations 1 and 2, the detected radiation fluxes from the PHO in different directions will vary by more than a factor of 30 (see equation 2 and Fig. 1a). Therefore, uniform scanning of the sky with the exposure determined by the PHO with the lowest SNR will be very inefficient in terms of time. Different parts of the sky must be observed with different exposures, allowing them to obtain approximately the same SNR values. Uniform scanning of the sky is possible in situation 3, especially for $\Delta T > 1$ yr.

4 Questions requiring further study

There are a number of issues that require further consideration in the context of the problem of detecting long-period comets colliding with the Earth. The authors intend to present the results of their research in subsequent publications.

4.1 Duration of one control surface review

The duration τ of a single survey of the control surface must be at least several times smaller than ΔT. Three measurements of the apparent positions of PHO are sufficient to determine its orbit (Neutsch and Scherer 1992). To obtain these data only from the spacecraft searching for PHO, 3 surveys of the control surface will be required, which will take 1–3τ time. However, in most cases, the possibility of an object colliding with the Earth can be excluded by 2 observations and even by 1 observation if the object has shifted during the exposure time. Orbits of detected objects can be determined by other telescopes (ground-based or space-based), in which case the hazard level of the object can be determined more rapidly.

Modern ground-based survey telescopes conduct sky surveys fairly quickly: ZTF surveys the accessible region of the sky in 1 day, LSST in 3 days. One can expect that a single sky survey from orbit will have a comparable duration. From this it is clear that the condition $\tau \ll \Delta T$ will be satisfied at $\Delta T \gtrsim 1$ month, i.e. for situations 2 and 3.

4.2 Registering objects of larger and smaller sizes

When conducting a control surface survey aimed at detecting a PHO with given d, A and ΔT, both closer and smaller objects with $d_n < d$ and $\Delta T_n < \Delta T$ and more distant and larger ones with $d_f > d$ and $\Delta T_f > \Delta T$ will be simultaneously registered. It is necessary to consider the possibility of separating these groups of objects.

4.3 Comets approaching the Earth from the Sun

Some dangerous comets remain at a distance of less than 30° from the Sun for a near-Earth observer during their entire flight within the control surface. In Fig. 2 such are two comet trajectories starting on the inner control surface. These objects are basically impossible to detect from Earth or a near-Earth spacecraft. The Chelyabinsk meteorite had a similar orbit.

To detect such objects, a spacecraft distant from Earth is needed. One possible location is the Lagrange point L_1 of the Sun–Earth system (Shugarov et al. 2018; Shugarov and Shustov 2022). Another location – near the Earth's orbit between the Earth and one of the triangular Lagrange points L_4, L_5 (Kuleshov et al. 2013).

Conclusion

1. It can be considered that the system of detecting dangerous objects among Near Earth Asteroids is developing successfully.
2. For guaranteed detection of 100 m dangerous comets 1 month before collision with Earth, a specialized spacecraft or group is required.
3. There are a number of issues that require further research.

References

Borovička J. (2015) IAU General Assembly. Meeting 29, id 2253831
CNEOS (2025) URL: https://cneos.jpl.nasa.gov/stats/totals.html
Kuleshov Yu.P., Egorov V.L., Misnik V.P., et al. (2013) Ecol. Bull. Sci. Centers Black Sea Econ. Coop. 2, 89
Millman J. R. (1961) Astron. Soc. Can. 55, 265
Neutsch W., Scherer K. (1992) Celestial mechanics: An introduction to classical and contemporary methods, Mannheim: BI Wissenschaftsverlag
Pitz A., Kaplinger B., Vardaxis G., ey al. (2014) Acta Astronautica 94, 42
Shugarov A.S., Shustov B.M. (2022) INASAN Sci. Rep. 7, 85
Shugarov A., Shustov B., Naroenkov S. (2018) Open Astron. 27, 132
Shustov B.M., Prokhorov M.E. (2024) Astron. Rep. 68, S126
Trigo-Rodríguez J.M. (2022) Asteroid Impact Risk: Impact Hazard from Asteroids and Comets (Impact Studies), Springer
Wikipedia (2017) URL: https://en.wikipedia.org/wiki/Category:Asteroid_surveys
Wikipedia (2020) URL: https://en.wikipedia.org/wiki/Category:Astronomical_surveys