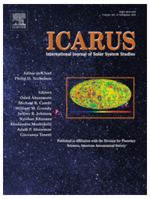
Icarus 000 (2017) 1–8

Contents lists available at ScienceDirect

Icarus

journal homepage: www.elsevier.com/locate/icarus



Detectability of Chelyabinsk-like impactors with Pan-STARRS

Marco Micheli[a,b,c,*], Richard J. Wainscoat[c], Larry Denneau[c]

[a] ESA SSA-NEO Coordination Centre, Largo Galileo Galilei, 1, 00044 Frascati (RM), Italy
[b] INAF-Osservatorio Astronomico di Roma, Via Frascati, 33, 00040 Monte Porzio Catone (RM), Italy
[c] Institute for Astronomy, University of Hawaii at Manoa, 2680 Woodlawn Dr, Honolulu, HI 96822, USA

ARTICLE INFO

Article history:
Received 2 April 2017
Revised 3 September 2017
Accepted 11 October 2017
Available online xxx

Keywords:
Near-Earth objects
Asteroids
Dynamics

ABSTRACT

In this work we present the results of our analysis of the detectability of an object in the size range of the recent Chelyabinsk impactor under the current discovery and follow-up capabilities, using the specific observational strategy of the Pan-STARRS survey as a reference point. We first discuss the observability of real-life cases inspired by the impact trajectories of 2008 TC_3, 2014 AA, the past Earth encounters with 2014 RC and 2015 TB_{145}, the upcoming fly-by of 2012 TC_4 and the Chelyabinsk event. We then expand our analysis with the investigation of synthetic impactors with realistic orbital distributions. Among the various conclusions of our analysis, we discuss how the time of first detectability of an object does not necessarily correspond to the moment when that same object can be recognized as an impactor. We also point out how objects discovered only a few days before impact can be immediately identified as impactors, partly thanks to the good astrometric quality that telescopes like Pan-STARRS currently achieve.

1. Introduction

The impact of a large (absolute magnitude $H \sim 27$) meteoroid near Chelyabinsk, Russia, has produced renewed interest in whether contemporary near-Earth asteroids surveys could detect similar objects before impact. The only two cases to date of an asteroid survey detecting an asteroid before impact are the much smaller 2008 TC_3 ($H \sim 30.3$), which was detected by the Catalina Sky Survey (hereafter CSS) approximately 20 h before impact (McGaha et al., 2008), and the even smaller ($H \sim 30.9$) 2014 AA, detected by the CSS approximately 19 h before impact (Kowalski et al., 2014). Brown et al. (2013) concluded that impacts by meteoroids similar in size to the Chelyabinsk object are actually much more frequent than previously recognized, happening on average a few times per century. Although no lives were lost from the Chelyabinsk event, the shockwave from the meteor produced widespread damage and many injuries (which could have been even more substantial had the impact trajectory been less shallow). The Chelyabinsk meteoroid approached Earth from a direction close to the Sun, and there was no possibility that any ground-based optical telescope could have detected it right before impact. It is inevitable that similar and larger impacts will occur in the future, and more than half of these will approach from a direction that is observable from the ground when the Sun is below the horizon, and so can be detected by ground-based telescopes (Farnocchia et al., 2012).

The core mission of the contemporary near-Earth asteroid surveys such as the Catalina Sky Survey (Larson et al., 2003) and the Pan-STARRS1 (Wainscoat et al., 2016) Near Earth Asteroid Survey (hereafter PS1) has been to find larger objects with $H \leq 22$ (diameter approximately 140 m or larger). An impact from an object of this size may be a catastrophic event causing the loss of many lives. If such an impact is predicted far enough in advance, efforts can be made to deflect the orbit of the asteroid to prevent the impact, or in the event that deflection is not possible, the region of impact can be evacuated before impact to reduce or eliminate loss of life.

Discovering and establishing the orbits of all near-Earth asteroids with sizes $H < 27$ is a task far beyond the capabilities of contemporary asteroid surveys. However, the contemporary asteroid surveys may be able to detect impactors that approach Earth from the night side, and provide some days of warning. This is one of the motivations for the ATLAS (Tonry, 2011) and the Fly-Eye (Cibin et al., 2012) telescopes that are presently being developed or recently began operations.

The capabilities of both the CSS and Pan-STARRS asteroid surveys are improving. A larger detector has been installed on the 1.5 m telescope of the CSS, and the second Pan-STARRS telescope (PS2) is being commissioned, and is expected to be fully operational later in 2017. It is expected that with these enhanced

---

[*] Corresponding author at: ESA SSA-NEO Coordination Centre, Largo Galileo Galilei, 1, 00044 Frascati (RM), Italy.
E-mail address: marco.micheli@esa.int (M. Micheli).

https://doi.org/10.1016/j.icarus.2017.10.010
0019-1035/

capabilities, both of these surveys will detect an increased number of small Earth impacting asteroids. In this paper, we examine the appearance of an impactor as it approaches Earth, including when it is first observable, and when it can be recognized as an object that is likely to hit Earth. Our simulations principally use the Pan-STARRS1 telescope's capabilities, but the results and conclusions can be extended to other surveys such as CSS and ATLAS.

2. Case studies of real objects

In the first part of this work we present the results of tests performed by using specific realistic impactors, outlining the basic observational challenges and peculiarities of an object in an Earth-crossing trajectory. In most cases, the computation of trajectories, orbits and impact circumstances included in this software have been performed using the software Find_Orb by Bill Gray.[1]

The first example is taken from the case of 2008 TC_3, the first known Earth impactor discovered while still in space (McGaha et al., 2008), which was predicted to fall in Northern Sudan (Farnocchia et al., 2017) and resulted in the Almahata Sitta meteorite fall (Jenniskens et al., 2009); in the same section we also quickly discuss the case of 2014 AA (Kowalski et al., 2014), the first object designated in 2014 which fell in the Atlantic ocean less than a day after discovery (Farnocchia et al., 2016a).

We then briefly discuss three other non-impacting cases, the close fly-by of 2014 RC, the large approacher 2015 TB_{145} found just before fly-by, and the return of 2012 TC_4, which present real-life examples of close-approach scenarios of objects with different sizes and warning times.

Our final case study is based on the orbit of the Chelyabinsk meteoroid itself, but assuming the object was coming from the opposition direction, where it would have been observable during the nighttime.

2.1. 2008 TC_3 and 2014 AA: two true impactors

For our first test, we simulated the approaching phase of an object with the same orbital elements (and therefore incoming trajectory) as 2008 TC_3, but with a different absolute magnitude of $H = 27$, compared with the value of $H = 30.3$ for the actual 2008 TC_3 asteroid. The choice of $H = 27$ is made because the goal of this work is to investigate the detectability of impactors in a size range around 10m to 30m, where the ground effects of an impact and possible associated airburst event could be significant in terms of ground damage and possible casualties, and for which the likelihood of such an impact in our lifetimes is significant.

We tested this scenario by computing a set of simulated observations for each night before the impact time. For each night, a set of four observations (called a "quad") was created, each separated by about 20 min, to simulate the usual observational pattern of the current Pan-STARRS solar system survey (Denneau et al., 2013); each observation point was chosen so that it corresponded to a position actually observable by Pan-STARRS (above the horizon and in night-time sky). Each observation was also randomly perturbed with astrometric noise, Gaussianly distributed with a standard deviation of $0.15''$ in right ascension and declination, comparable with the typical current astrometric accuracy of Pan-STARRS observations (Milani et al., 2012; Tholen et al., 2013; Vereš et al., 2017). Other observational parameters, such as a limiting magnitude of about $V = 22$, and a projected angular speed limit of 10°/day, were also taken from the current survey properties of Pan-STARRS.

Under these assumption, the synthetic object presented above would have crossed a threshold of magnitude $V = 22$ approximately 20 days before the impact time, and around that time it would have been detectable by Pan-STARRS not far from the opposition region, which is also the area where the survey spends most of its time, especially around the weeks of reduced moon interference. At that time the object would still be more than 10^7 km away from the Earth. However, an interesting point becomes immediately evident. Around this time the object would have had an angular speed of about 0.25°/day, which is not peculiar in the opposition region, and it is shared by many uninteresting main-belt objects in that area.

This fact is emphasized by computing the digest score of the object at that time, the key quantity used by the Minor Planet Center[2] to evaluate if an object is worth additional follow-up as a possible NEO candidate, based on the vector of the object's sky motion in comparison to the typical motion of main-belt asteroids in that area of the sky; our target would have scored a digest value of about 10, definitely within the range of non-interesting objects, not worthy of additional follow-up efforts.

This point is the first key result of this analysis, and it will be discussed again below. Interesting large impactors may become observable quite early with the typical telescope apertures of the current surveys, but they may not be recognized as such at the very beginning, because of their unremarkable motion.

The following key milestone of our candidate would not have been crossed until about 11 days before impact. If discovered around that time the object would have already reached a magnitude of $V \sim 20.5$, even with a still reasonably slow motion of 0.5°/day. However, around this time the combination of a faster motion and a brighter magnitude would have been enough to increase the MPC digest score to about 90, sufficient to be deemed worthy of additional follow-up, and therefore posted on the NEO Confirmation Page[3] (NEOCP), where other observers worldwide could have noticed it and targeted it for follow-up observations.

However, in 2–3 days the situation would become much more clear. The object would now have a magnitude of $V \sim 20$, and would also score 100 on the MPC digest score, making it a high priority candidate for follow-up.

This is also approximately the time when the trajectory of the object within the four observation tracklet starts to show the first signs of curvature due to the parallax introduced by the nightly rotational motion of Earth. As a result, the best-fit orbit going through the four observations would depart slightly from a great circle, and start displaying residuals of the order of $0.2''$ or so. Although this effect may be noticeable, and its non-random nature may be evident to a human investigation of the pattern of the astrometric residuals, a more routine automated analysis that does not take into account additional information, such as curvature and trends, may still conclude that such anomalies are within the expected astrometric error bars of the positions, and it would therefore not be considered significant. Under these circumstances, manual verification of the astrometric quality, by inspecting the actual images and checking for anomalies (artifacts, poor seeing, overlaps and so on) may also help distinguishing between real and spurious cases.

Around this time we would probably know almost for sure that a close approach of the object with Earth will occur, but from the single discovery tracklet we would not have enough information to determine that an impact is going to happen. The object would likely be flagged as of interest by the Scout imminent impactor tool[4] developed by Farnocchia et al. (2015, 2016b). In fact, tools like Scout, which use the entire information included in the curvature of the observations, can identify possible candidate impactors

---

[1] https://www.projectpluto.com/find_orb.htm.

[2] http://www.minorplanetcenter.net/iau/NEO/PossNEO.html.

[3] http://www.minorplanetcenter.net/iau/NEO/toconfirm_tabular.html.

[4] https://www.cneos.jpl.nasa.gov/scout/.

Please cite this article as: M. Micheli et al., Detectability of Chelyabinsk-like impactors with Pan-STARRS, Icarus (2017), https://doi.org/10.1016/j.icarus.2017.10.010