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Detection of Earth-impacting asteroids with the next generation all-sky surveys

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ABSTRACT

We have performed a simulation of a next generation sky survey's (Pan-STARRS 1) efficiency for detecting Earth-impacting asteroids. The steady-state sky-plane distribution of the impactors long before impact is concentrated towards small solar elongations (Chesley, S.R., Spahr T.B., 2004. In: Belton, M.J.S., Morgan, T.H., Samarashinha, N.H., Yeomans, D.K. (Eds.), Mitigation of Hazardous Comets and Asteroids. Cambridge University Press, Cambridge, pp. 22–37) but we find that there is interesting and potentially exploitable behavior in the sky-plane distribution in the months leading up to impact. The next generation surveys will find most of the dangerous impactors (>140 m diameter) during their decade-long survey missions though there is the potential to miss difficult objects with long synodic periods appearing in the direction of the Sun, as well as objects with long orbital periods that spend much of their time far from the Sun and Earth. A space-based platform that can observe close to the Sun may be needed to identify many of the potential impactors that spend much of their time interior to the Earth's orbit. The next generation surveys have a good chance of imaging a bolide like 2008 TC_3 before it enters the atmosphere but the difficulty will lie in obtaining enough images in advance of impact to allow an accurate pre-impact orbit to be computed.

1. Introduction

Throughout most of human history it was not understood that the Earth has been battered by large asteroids and comets and that the impacts and subsequent environmental changes have serious consequences for the survival and evolution of life on the planet. But in the past ∼50 years more than 170 impact structures have been identified on the surface of the Earth (Earth Impact Database, 2008. http://www.unb.ca/passc/ImpactDatabase/index.html). Were it not for the Earth's protective atmosphere, oceans, erosion and plate tectonics, the surface of the Earth would be saturated with impact craters like most other atmosphereless solid bodies in our Solar System. While the impact probability is now relatively well understood as a function of the impactor size (*e.g.* Brown et al., 2002; Harris, 2007) this work addresses specific questions related to discovering impacting asteroids before they hit the Earth. In particular, we build upon the work of Chesley and Spahr (2004) and determine the sky-plane distribution of impacting asteroids before impact and the effectiveness of the next generation large synoptic sky surveys at identifying impactors.

The first surveys to target near-Earth objects (NEO) (Helin and Shoemaker, 1979), asteroids and comets with perihelion <1.3 AU, provided the first look at their orbit and size distribution and allowed the first determination of the impact rate from NEO statistics (Shoemaker, 1983) rather than crater counting on the Moon. These pioneers heightened the awareness of the impact risk and gave rise to the current generation of CCD-based asteroid and comet surveys (Stokes et al., 2002) such as Spacewatch (Gehrels, 1986), LINEAR (Stokes et al., 2000), LONEOS (Koehn and Bowell, 1999), NEAT (Pravdo et al., 1999), and the current leader in discovering NEOs, the Catalina Sky Survey (CSS) (Larson et al., 1998). These programs benefitted from the elevated impact risk perception when in 1998 the U.S. Congress followed the recommendations of (Morrison (1992)) and mandated that the U.S. National Aeronautics and Space Administration (NASA) search, find and catalog ⩾90% of NEOs with diameters larger than 1 km within 10 years. That goal will probably be achieved within the next few years. The residual impact risk is mainly due to the remaining undiscovered large asteroids and comets (Harris, 2007) but Stokes et al. (Stokes et al., 2004. http://neo.jpl.nasa.gov/neo/report.html)

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suggest that the search should be expanded to identify ⩾90% of potentially hazardous objects (PHO) by 2020.[1]

Stokes et al. (Stokes et al. 2004. http://neo.jpl.nasa.gov/neo/report.html) showed that the extended goal cannot be achieved in a reasonable time frame with existing survey technology. The search needs to be done from space (rapid completion but at high risk and high cost) or from new ground-based facilities (slower completion but lower risk and lower cost). Their recommendation dovetailed nicely with the Astronomy and Astrophysics Survey Committee (2001) Decadal Report that made a strong case for the development of a large synoptic survey telescope (LSST) that would provide the necessary depth and sky coverage to identify the smaller PHOs while also satisfying the goals of other fields of astronomy.

There are currently a few candidates for a large synoptic survey telescope. The most ambitious is an 8.4 m system being designed by the eponymous LSSTC (the LSST Corporation) that anticipates beginning survey operations in 2016 in Chile. With a $\sim$9 deg^2 field of view and 15 s exposures, simulations suggest that their system could identify $\gtrsim$90% of PHOs in 15 years (Ivezić et al., 2007). A more modest LSST known as the Panoramic Survey Telescope and Rapid Response System (Pan-STARRS, Jedicke et al., 2006) will be composed of four 1.8 m telescopes (PS4) and is expected to be located atop Mauna Kea in Hawaii. A prototype single telescope for Pan-STARRS known as PS1 should begin operations in mid-2009 from Haleakala, Maui. With a $\sim$7 deg^2 field of view, the excellent seeing from the summit of Mauna Kea, and the use of orthogonal transfer array CCDs (Burke et al., 2007) for on-chip image motion compensation, the Pan-STARRS system will be competitive with and completed earlier than the LSSTC's system.

The next generation survey telescopes have the potential to be prolific discoverers of PHOs but Earthlings are not so much concerned with statistical impact risk calculated from PHO orbital distributions as they are interested in whether an impact event will occur. The statistical risk of a house burning down may seem inconsequential until you consider the actuality of *your* house being incinerated. Similarly, while Harris (2008) has calculated that expected fatalities due to an unanticipated asteroid impact have dropped from $\sim$1100/year before the onset of modern NEO surveys to only $\sim$80/year now, as a species we would like to know whether one of the fatality inducing impacts will take place *this* century. Thus, this work concentrates on the detection of objects that may impact the Earth in the next hundred years.

Following Chesley and Spahr (2004) we concentrate on the subset of PHOs that are in fact destined for a collision with the Earth. They showed that long before impact the impactors' steady state sky-plane distribution is concentrated on the ecliptic and at small solar elongation. We extend their analysis and find that the sky-plane distribution of impactors has interesting and potentially useful structure in the time leading to collision. We also study the capabilities of one next-generation survey (PS1) at identifying the impactors well before collision. In particular, we will answer the following questions: How different are the orbital characteristics of the impactor population and current NEO and PHO models? What is the survey efficiency for identifying asteroids on a collision course with the Earth as a function of their diameter? How much warning time will be provided before the impact? How accurate is the orbital solution prior to impact? How does the MOID[2] evolve in time and is the current definition of a PHO consistent with flagging dangerous objects? What are the orbital properties of objects that are not found? Are there methods to improve the efficiency of identifying impactors? Given the size-frequency distribution of NEOs what is the probability that PS1 will actually identify an impactor and what will be its most probable size?

2. Synthetic Earth-impacting asteroids

Our synthetic impactor population model is described in detail in Chesley and Spahr (2004). Here we provide a brief summary of the technique.

We created $\sim$130,000 impactors based on the NEO population developed by Bottke et al. (2000) and Bottke et al. (2002) hereafter referred to as the Bottke NEO Model. The model incorporates objects from both asteroidal and cometary source regions but has at least two problems that affect its utility for creating an impactor population: (1) it assumes that the orbit distribution of NEOs is independent of their diameter and (2) it provides the (a,e,i,H) (semi-major axis, eccentricity, inclination, and absolute magnitude) distribution for NEOs on a coarse grid that is not suited to the narrower range of orbital elements of the impacting asteroids. However, there are few options to use as starting points for developing an impactor population and we will compare our impactor population's orbit distribution to the known small impactor population to understand the limitations of our technique.

To generate the impactors NEOs were randomly selected from the Bottke NEO model and assigned random longitudes of ascending node and arguments of perihelion. Orbits with a MOID small enough to permit an impact were saved as *potential impactors* and then filtered according to their likelihood of impact to obtain the final set of impactors. The likelihood is the fraction of time that an object spends in close proximity to the Earth's orbit. *i.e.* orbits with a small velocity relative to the Earth tend to have shorter impact intervals and higher intrinsic impact probabilities. Higher likelihoods received higher weighting in the selection. If an orbit was chosen as an impactor then a year of impact was randomly selected between 2010 and 2110—the date of collision is already randomly fixed by the longitude of the node at impact. To this point, the process assumed a two-body asteroid orbit with no planetary perturbations. The final step was to ensure an impact under the influence of all the perturbations in a complete Solar System dynamical model. This was done by differentially adjusting the two-body argument of perihelion (ω) and orbital anomaly to reach a randomly selected target plane coordinate on the figure of the Earth. The final result is an osculating element set that leads to an Earth impact when propagated with the full dynamical model. The full set of impactors generate about three impacts per day uniformly distributed over the globe with an average separation of about 70 km.[3]

This technique preferentially selects objects on Earth-like orbits out of the Bottke NEO model but Brasser and Wiegert (2008) show that objects do not remain long in these types of orbits. This is not a problem except in the sense addressed above—that the Bottke NEO model is provided on a relatively coarse grid—because the NEO model already accounts for NEO 'residence times' on all types of NEO orbits. However, since we assume a flat distribution of NEO orbit elements within the (a,e,i) bin corresponding to Earth-like orbits it is likely that we generate fractionally more of the extremely Earth-like orbits than exist in reality.

As shown by Chesley and Spahr (2004) and in Fig. 1 there are important differences between the impactor population and the NEOs. The impactors have orbits with lower semi-major axis, inclination and eccentricity. This has the effect of decreasing the Earth encounter and impact velocity (v_∞ and v_{imp} respectively) for the

[1] A PHO is an object with absolute magnitude $H \leqslant 22$ ($\sim$140 m diameter) on an orbit that comes within 0.05 AU of the Earth's orbit.

[2] Minimum Orbital Intersection Distance.

[3] Gallant et al. (2006) use a superior (but much more time consuming) technique to generate an even more unbiased impactor population from the Bottke NEO model and confirm that the latitude and longitude distribution of impact locations is flat to within a few percent when averaged over all impactors and times of year.