4th IAA Planetary Defense Conference – PDC 2015
13-17 April 2015, Frascati, Roma, Italy

IAA-PDC-15-01-04
RECENT ENHANCEMENTS TO THE NEO OBSERVATIONS PROGRAM: IMPLICATIONS FOR PLANETARY DEFENSE

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Keywords: *NEOs, observations, planetary defense, NASA*

Extended Abstract: NASA's NEO Observations Program finds, tracks, and characterizes asteroids whose orbits bring them within approximately 50 million kilometers of Earth's orbit about the Sun. Recent enhancements to the Program have led to ~45% increase in the discovery rate of near-Earth asteroids (NEAs) over the past year. Since the program's inception in 1998, NASA has funded several universities and space institutes to upgrade and operate existing 1-meter class telescopes to conduct the search for NEOs. Of critical importance to the effort is the Minor Planet Center (MPC) of the Smithsonian Astrophysical Observatory, where automated systems process [in near real-time] observations produced by the search teams. The NEO Office at the Jet Propulsion Laboratory (JPL) determines precise orbits for the objects. Both JPL and the MPC utilize processes and procedures for NEO orbit determination and prediction that are sanctioned and monitored by the International Astronomical Union (IAU), and produce data catalogues on small bodies in the Solar System that are utilized world-wide by the astronomical community. The Program's enhancements have added (and will continue to add) capabilities to find potentially hazardous objects (PHOs). With several survey enhancements underway and new surveys coming on line within the next few years, the NEO discovery rates should at least double.

Figure 1: 1.52-meter (60") Cassegrain reflector *f*/2 prime focus has a 1° field-of-view, detecting down to 22nd magnitude objects. Located atop Mt. Lemmon, this telescope (G96) is one of three co-located ground-based facilities that comprise the Catalina Sky Survey. G96 is also used for astrometric follow-up and physical observations NEOs (University of Arizona, CSS).

Within the government of the United States, NASA is responsible for coordinating the NEO detection and threat information from all organizations within the world-wide NEO community. NASA has instituted communications procedures, including policies with regard to public release of information. NASA's notification procedures are set into motion only after the necessary observations, analyses, and characterization efforts have been utilized in order to determine that a space object represents a credible threat. Depending on the level of risk (and urgency) this may unfold for several years after the initial detection of the body. This process entails various combinations of:

- Increased monitoring;
- Cross-checks of potentially hazardous trajectories as needed;
- Accelerated observations and orbit determination if potential hazard is near-term.

Upon notification by NASA of a potential NEO threat on U.S. territory, the Federal Emergency Management Agency (FEMA) will be the lead entity to notify the appropriate Federal, regional and local authorities to manage the emergency response. In the event of an impact threat beyond the territory of the United States, the U.S. Department of State will facilitate the international notification efforts to minimize loss of human life and property and assist recovery efforts (OSTP, 2010).

Figure 2: Existing worldwide observing network for NEOs (both detection and follow-up characterization).

Today, NASA funds three premier ground-based capabilities: the Lincoln Near-Earth Asteroid Research (LINEAR) project, the Catalina Sky Survey (CSS), and the Panoramic Survey Telescope and Rapid Reporting System (Pan-STARRS). LINEAR has transitioned to the larger Space Surveillance Telescope (SST) and currently holds the record for most observations submitted to the MPC in 2015.[1] Pan-STARRS-1 is now dedicated to NEO efforts and its discovery rate is up 70% over the previous year. While the CSS discovery rate remains the same, its camera will be upgraded this year. These survey efforts are increasingly yielding close encounter predictions (i.e., < 0.001 AU) and some small Earth impact events (e.g., 2008 TC_3 and 2014 AA). Such encounters provide opportunities for NASA's Infrared Telescope Facility (IRTF) to make spectral measurements; or, in the case of planetary radars at Arecibo and Goldstone, refine the orbit of the object with great precision and even "image" the small primitive body.

Most recently, the *Wide-field Infrared Survey Explorer* (*WISE*)[2] was reactivated with a prime mission of detecting and characterizing NEOs. *WISE* is in Sun-synchronous, near-polar inclination (97.5°) orbit around the Earth. The 'NEOWISE-R' project utilizes *WISE* in 'warm mode' (i.e., at 3.4 and 4.6 μm). In conjunction with ground-based follow-up, this unique dataset has set limits on population statistics, orbital parameters, approximate sizes, and initial compositional knowledge of the asteroid population (Mainzer *et al*., 2014[a,b]). Since its reactivation in late 2013, NEOWISE-R has observed more than 250 NEAs; discovered 47 new NEOs (and 3 comets); and observed in excess of 11,000 other asteroids (Nugent *et al*., 2015).

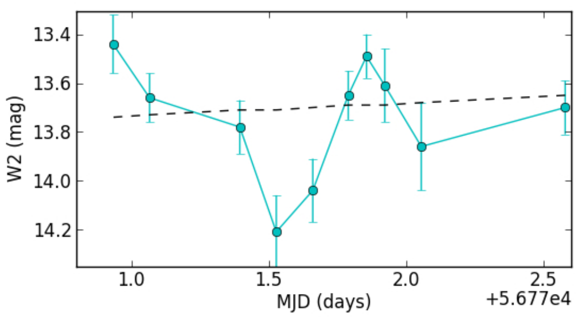

Figure 3: Lightcurve data from NEOWISE-R shows that 2014 HQ_{124} rotates ~once every 20 hours and that the NEO is clearly elongated (0.8 magnitude change in amplitude) and the measured rotation period agrees with the radar data (Mainzer, 2014[c]).

A signature example of initial detection, follow-up astrometry, and characterization is the discovery of 2014 HQ_{124}. Over 23-24 April 2014, NEOWISE discovered the NEA. Rapid follow-up observations and orbit determination showed the asteroid would pass within 3.3 lunar distances (~1.3 million km) of the Earth; traveling from a southerly to a northward declination. The first observatories to perform the ground-based follow-up included RAS Observatory, Moorook, South Australia; Gemini South Observatory, Cerro Pachón (near Vicuña), Chile; and Mt. John Observatory, South Island, New Zealand.

The detailed follow-up astrometric observations are key in order to more efficiently plan and obtain planetary radar observations. If an NEO has a relatively close approach to the Earth, the Arecibo and Goldstone planetary radars are able to refine the orbit of the object with great precision and even ''image'' the small primitive body. These planetary radars can image these bodies with resolutions as fine as ~4 meters (depending upon the signal-to-noise and the proximity of the passage to the Earth). This can reveal the basic shape of the object and, in turn, determine size, spin orientation, whether it was part of a multiple system (i.e., with binary or tertiary companion bodies – 'moonlets'), as well as large-scale surface characteristics (i.e., boulders, craters, etc.). Working together, the Goldstone and Arecibo dishes obtained bistatic radar observations of 2014 HQ_{124} on 8 June 2014 (day of closest approach) revealing concavities, embedded boulders, and a general shape of the asteroid.

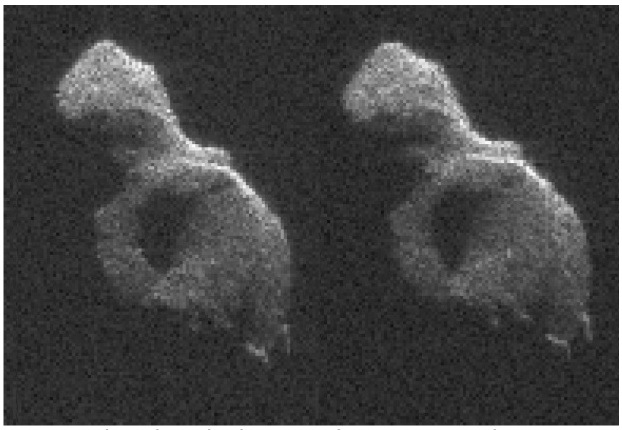

Figure 4: Bi-static radar images of 2014 HQ_{124} taken on 8 June 2014 (day of closest approach) at a distance of ~1.3 million km. These unique radar measurements indicate this NEA is ~370 meters along its long axis, has a ~20-hour rotation period, and may be a contact binary. Several large boulders appear to be imbedded into the main body (Benner *et al*., 2014).

The rapid response after discovery (as described in the case of the example of the discovery and subsequent follow-up of 2014 HQ_{124} last year) is critical for the physical characterization of PHOs. The Goldstone and Arecibo planetary radars are essential characterization assets for NEAs of interest because these facilities provide accurate estimates of size, spin state, physical shape as well as yield precise orbit determination.

[1] http://www.minorplanetcenter.net/iau/special/CountObsByYear.txt
[2] *WISE* was launched on 14 December 2009 and sensitive in four channels: 3.4, 4.6, 12, and 22 μm. The spacecraft was placed into hibernation on 1 February 2011 and resumed 'warm' operations in December 2013; 3.4 and 4.6 μm functional in 'warm mode.'

NASA's Infrared Telescope Facility (IRTF), located atop Mauna Kea, Hawaii, has a unique tool in the SpeX instrument (a spectrograph) to better determine bulk compositional knowledge of NEOs – another significant characteristic to consider for planetary defense aspects. Figure 5 (below) is an example of an infrared (IR) spectrum obtained by Reddy (2015[a]) of 2014 WC_{201} – a Chelyabinsk-sized asteroidal body.

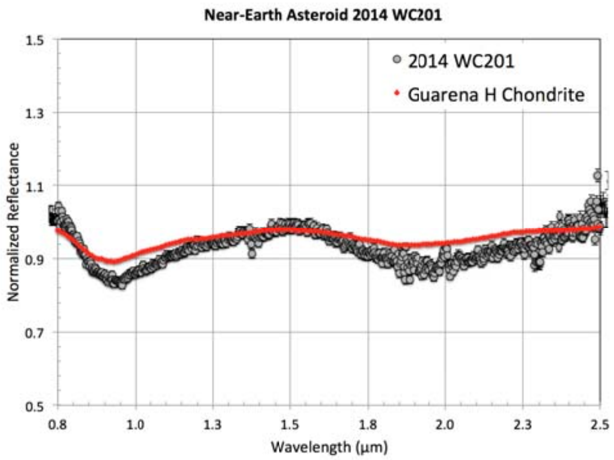

Figure 5: Near-IR spectrum (IRTF SpeX) of 2014 WC_{201} showing absorption bands at 1- and 2-μm due to olivine and pyroxene. This NEA is ~17-meters across and likely an H-type chondrite. The Guareña [H-type] chondrite spectrum is overlaid in red for comparison (Reddy *et al*., 2015) whose parent body might be the Main Belt asteroid 6 Hebe (Gaffey & Gilbert, 1998).

In addition to supporting the astronomical observations of NEOs, the NEO Observations Program also works jointly with FEMA to conduct emergency response exercises involving impact scenarios. To date, two tabletop exercises have been conducted to acquaint several U.S. government agencies with the nature and evolution of an impending asteroid impact within the continental United States and to assess whether and how current processes and procedures for disaster warning and response might be employed in such an emergency (Ailor *et al*., 2013; 2014).

The scenario for the second exercise in 2014 involved an asteroid, ~140-300 meters in size, discovered ~7 years before predicted impact. This advance notice enabled the development and execution of a space mission campaign to deflect the object away from an Earth impact trajectory. In this simulated scenario, the deflection mission was only partially successful: a major portion of the target object was deflected, but a ~50-meter fragment broke off and remained on a collision course with Earth. Though the 50-meter remnant was observed almost two years before impact, there was insufficient time to attempt a second deflection campaign. For the exercise, the fragment was predicted to impact somewhere within a narrow region extending through Texas and into the Gulf of Mexico. As the scenario evolved, the exercise team provided updates on the state of knowledge of the approaching asteroid, the design and results of the deflection mission, possible regions on Earth that might be affected by an impact, and the nature and consequences of the anticipated air blast and impact insults. While this year's impact scenario is realistic, details of an actual impact threat and its evolution would be unique, as each asteroid, and its orbit, is unique. This scenario illustrates the type of information that would be available should a real impact threat develop and how entities such as the recently established International Asteroid Warning Network (IAWN) and Space Mission Planning Advisory Group (SMPAG, pronounced 'same page') would be engaged in a potential real-world impact event.

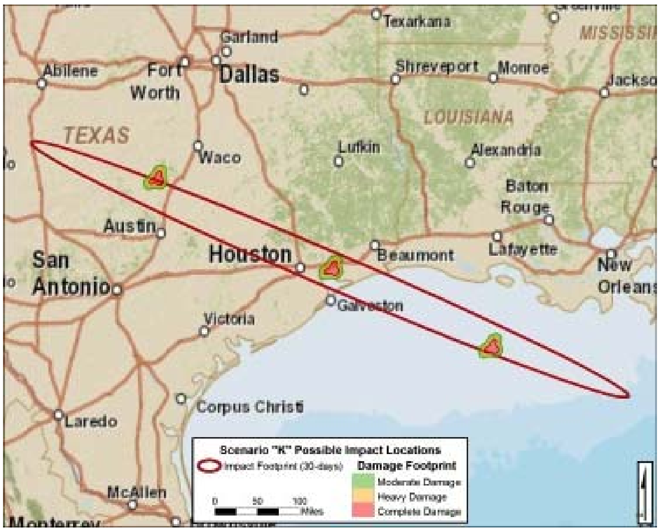

Figure 6: For the second FEMA-NASA joint tabletop exercise showing impact ellipse and damage footprints within that ellipse at 30 days before impact.

The NEO Observations Program recently initiated a new set of tasks regarding planetary defense with NASA's Ames Research Center (ARC) which involve the:

- collection of known characterization data on NEOs;
- physics-based modeling of atmospheric entry (and potential for subsequent breakup);
- modeling of Earth surface impacts; and
- physics-based impact risk assessment.

These objectives are inter-related and involve both domestic and international organizations to help address these issues for the planetary defense community. The first task is focused on building validated models of the physical properties of potentially hazardous asteroids (PHAs) based on astronomical observations and what can be learned from meteoritic collections. The second part will extend existing NASA physics-based atmospheric entry technology codes so they can reliably predict environments for the more severe entries by small asteroids (up to ~20 km/sec entry speeds). This also seeks improved understanding of fundamental processes that occur during airbursts. The third part is focused on predicting the near field effects caused by airbursts (including land and water). The final objective is to better understand the minimum size PHAs that would require in-space mitigation action to be taken and therefore the associated lead-time required for their detection. (Conversely, this will also determine the maximum size PHA whose effects could be mitigated by terrestrial civil defense measures.)

In the past year, data gathered by other U.S. government sensors were released to NASA. Figure 7 below is a global map of bolides and shows that these small impacts are frequent and random. The dataset spans over two decades (1994-2013) and is released for use by the science community. Over this 20-year interval, U.S. government assets recorded at least 556 bolide events of various energies. In this Mercator-projection map, the size of the orange dots (daytime events) and blue dots (nighttime events) are proportional to the optical radiated energy of the impact event measured in billions of Joules (GJ) of energy. An approximate conversion between the measured optical radiant energy and the total impact energy can be made using an empirical relationship provided by Brown *et al*., (2002). For example the smallest dot on the map represents 1 GJ of optical radiant energy, or when expressed in terms of a total impact energy the equivalent of about 5 tons of TNT explosives. Likewise, the dots representing 100, 10,000 and 1,000,000 GJ of optical radiant energies correspond to impact energies of about 300 tons, 18,000 tons and one million tons of TNT explosives respectively.

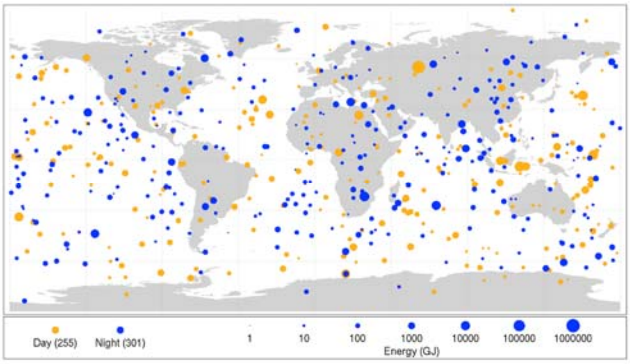

Figure 7: Distribution map of small asteroids that impacted the Earth's atmosphere from 1994-2013. The daytime Chelyabinsk event near the Ural Mountains is evident (NASA).

The largest impact event recorded during over this two-decade interval was the 15 February 2013 impact over Chelyabinsk, Russia releasing about 500 kilotons (kT) of equivalent TNT. That asteroid was ~17 to 20 meters across, fragmented and broke apart at ~30 km altitude (Brown *et al*., 2013).

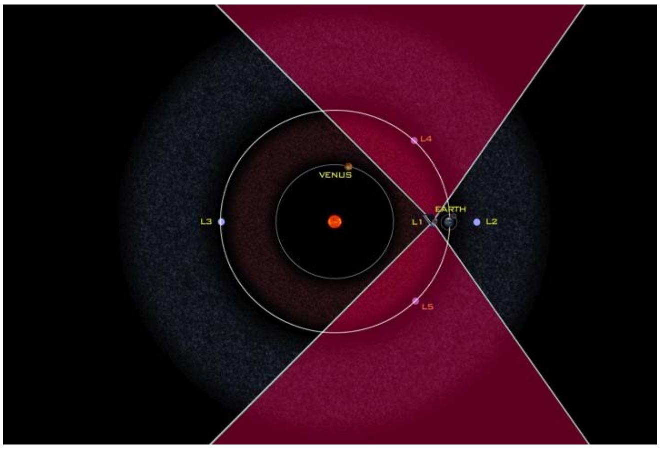

Figure 9: A depiction of the field(s)-of-regard of a space-based IR survey telescope at SEL_1. Such a telescope looks at the so-called 'sweet spots' for objects leading and trailing the Earth in its orbit about the Sun to find PHOs and assess the potential threat they pose (NASA GSFC).

Many NEOs have long synodic periods. Earth-based observations are geometrically limited in finding such bodies as they may linger within the vicinity of the Earth for several years if not decades. Due to their long synodic periods of several decades and longer, the work-around to this geometric observing handicap is a deep space telescopic NEO survey mission. That asset could be placed at either Sun-Earth-LaGrange point (SEL_1 or SEL_2) or, in a Venus-like orbit about the Sun looking outward. If this crucial first step proceeds to implementation, a more complete catalog of NEOs could be used to assess the present-day risk of impact events. The further side benefits of such a survey include the foundational solar system science and low Δv targets for potential spacecraft missions.

There is a considerable amount of planetary "jetsam and flotsam" – the remnants left over from the formation of our solar system – that, over time, have dynamically evolved to orbits that bring them close to the Earth. The U.S. government established direction for NASA regarding the detections of NEOs. The initial objective (which has become known as the Spaceguard Survey) directed NASA to find 90% of all NEOs 1 km and larger. That goal has been met. The updated objective, which is part of the NASA Authorization Act of 2005, directs NASA to track 90% of NEOs 140 meters in diameter or greater by 2020. At the current pace, this second mandate will not be met in that timeframe. However, a space-based IR survey [away from the vicinity of low-Earth orbit] would accelerate the discovery rate while providing rough compositional knowledge of these primate denizens of the solar system. There is perhaps no greater gift that the space agencies of the world could provide humanity than to know the time and place of an impact event so that we may adequately prepare our response to prevent planetary disaster.

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