Looking at the surface of our Earth, we can see scars of ancient impacts from asteroids in places like Barringer crater in Arizona or Chicxulub crater in the Yucatan. Within the past 100 years, the Earth has seen a meteorite explode in the air over Tunguska in Siberia, devastating a large area in the tundra, as well as many much smaller meteorites, such as the Chelyabinsk meteorite in 2013 that caused extensive property damage. These are the result of collisions between the Earth and the large population of much smaller near-Earth objects (NEOs).

In order to assess the risk from these NEOs, they have been discovered and followed by a number of dedicated astronomical surveys over the previous few decades. In order to extend our reach to ever-smaller but still potentially dangerous objects, a number of space and ground-based systems have been recently proposed. The largest of the planned Earth-based facilities, the Large Synoptic Survey Telescope (LSST), has just entered its construction phase after a decade of design and development.

NEOs are formally defined as objects with orbits that bring them to within 1.3 astronomical units (AU) from the Sun. An astronomical unit is defined as the mean Sun–Earth distance of 150 million km, and corresponds to about 400 times the Earth–Moon distance. NEOs are asteroids, small bodies composed predominantly of stony material ejected from the main asteroid belt between Mars and Jupiter due to gravitational and non-gravitational perturbations to their orbits, and migrating closer to Earth. Depending on details of their current orbits, NEOs are further classified into: the Atiras, whose orbits are enclosed by Earth’s orbit; the Atens and the Apollos, which cross Earth’s orbit; and the Amors, whose orbits enclose Earth’s orbit. There are about 1,000 NEOs with diameters larger than one kilometre, and the largest one is 35 km across (asteroid 1036 Ganymed). The typical lifetime of a NEO is only a few million years. NEOs are destined to collide with the Sun or a planet, or suffer another perturbation that ejects them from the solar system.
About 20 per cent of NEOs, the potentially hazardous asteroids (PHAs), are in orbits that pass sufficiently close to Earth's orbit, to within 0.05 AU (about 20 times the Earth–Moon distance, or about 1,000 Earth radii), that orbital perturbations with timescales of a century can lead to intersections and the possibility of collision. Formally, only the Atens and the Apollos have trajectories that cross Earth's orbit. However, the orbits of Atiras and Amors may change in the future. A collision with an object of one-kilometre diameter or more would release energy comparable to the explosion of all the world's nuclear weapons and have catastrophic consequences for life on Earth. Such collisions happen about once or twice every million years. Smaller objects are more numerous and collisions with 100-metre-wide or larger objects happen about once every 100,000 years. The main mode of inflicting damage for these smaller objects is large tsunamis. Very small asteroids with sizes of a few metres impact Earth about once a year. However, most objects smaller than about 20–30 metres burn up in the Earth's atmosphere and don't reach the ground.
Phobos, one of Mars’s two tiny moons, is believed to be an asteroid captured by Mars’s gravity. Orbiting at around 5,800 km above the surface, Phobos will eventually be shattered by the gravitational tidal forces.

Aware of the asteroid collision risk, the US Congress directed NASA, in December 2005, to implement a NEO survey that would catalogue 90 per cent of NEOs with diameters larger than 140 metres by 2020 (this has typically been interpreted as applying to 90 per cent of all PHAs). The deadline was chosen to be 15 years after signing the mandate, which at the time seemed a reasonable period to build a system (either space or Earth-based) to catalogue these PHAs. The size limit and 90 per cent completeness level were chosen through a careful calculation of potential risks from impactors, weighed against the increasing costs of detecting smaller and smaller objects, as well as a consideration for previous cataloguing efforts.

The population of larger NEOs and PHAs is now fairly well known, thanks to discovery and tracking efforts from previous and ongoing surveys. Ground-based Spacewatch, LINEAR, the Catalina Sky Survey and Pan-STARRS, as well as space-based NEOWISE, have already come close to identifying 90 per cent of all PHAs larger than one kilometre in diameter (NASA’s so-called Spaceguard goal), using modest-sized (less than two-metre) telescopes. Using the detections coming from these and other telescopes, NASA maintains an automated collision monitoring system called Sentry that continually scans the most current asteroid catalogue for possibilities of future impact with Earth over the next 100 years. Currently, there are no likely impactors.
The field of view of the Large Synoptic Survey Telescope (LSST)

Figure 1 summarises the extent of the LSST search region for NEOs and gives an example of a simulated NEO (orbital parameters are taken from a real object, but size and brightness are assumed much smaller in simulations) that was easily discovered in the simulated survey. We emphasise that the LSST search region for NEOs extends all the way in to the orbit of Venus and is not limited to the volume of space outside the orbit of the Earth from the Sun.

It is estimated that there are about 50,000 NEOs larger than 100m, with an uncertainty that could be as large as a factor of two. Extrapolation to smaller sizes is even more uncertain. Predictions for the number of NEOs larger than 10m are on the order of a million. On the assumption that there are approximately 100,000 objects of 50–100m, LSST could discover about 2,000 of them during its very first year of operation. Current NEO warning systems would detect it only five days in advance.

Perhaps more importantly, LSST would also detect such an object during three prior close approaches and thus would be able to predict the final close approach. However, detecting such small objects is by no means easy, either from ground or space, and no firm guarantees can be made due to our limited knowledge of the small-size end of the NEO population. For example, another 50-metre object, with the orbit shown in the top right panel in Figure 2, would be detectable only once by LSST during a 10-year period, when it’s close enough to Earth to become brighter than LSST sensitivity. The plot of its orbit shows that a space telescope in a Venus-like orbit staring at Earth would not detect it at all since its relative distance would remain 0.3 AU or larger, as opposed to ~0.01 AU distance when observed from Earth (unless that space instrument is significantly more sensitive than the missions currently proposed).

Another difficult case is shown in the bottom right panel in Figure 2: neither LSST nor a space telescope in a Venus-like orbit staring at Earth would discover it during 10 years because its synodic period is much longer than 10 years and it manages to ‘hide’ behind the Sun during the simulated survey. To discover such objects, LSST would have to survey the sky much longer than 10 years!

This is an edited version of a diagram from the 2010 National Research Council study Defending Planet Earth: Near-Earth Object Surveys and Hazard Mitigation Strategies. The addition includes the projection of the LSST search region for solar system objects onto the Ecliptic plane (red lines). The purported ‘Nominal search region available from Earth’ marked in the original version is much smaller than will be achieved by LSST.

Simulated NEO orbit

This shows an example of a simulated NEO orbit over a 10-year period in a rotating heliocentric system such that Earth (blue dot) is fixed at x=0, y=1. The blue circle shows one astronomical unit distance from the Sun (yellow dot). The magenta line shows the limiting distance for LSST detecting a 140-metre object. The closest solar elongations are at 45° and are tangential to the orbit of Venus. This object was easily recovered in the simulated survey due to its many detections. For larger objects, the discovery distance limit with LSST search region extends well beyond the outer edge of the main asteroid belt.
for that time period. The only object for which an eventual collision cannot be strongly ruled out is asteroid (29075) 1950 DA, with a possible (but not very likely) impact event in the year 2880.

However, to reach the 90 per cent completeness level for the smaller PHAs with diameters of 140 m requires larger telescopes, with larger cameras, than are currently deployed in NEO-hunting. A cost-effective measure is a 10-metre class, ground-based observatory equipped with a large camera and sophisticated and robust data processing system. LSST is such a system, and sophisticated simulations of NEO/PHA populations coupled with realistic observing conditions have shown LSST is capable of fulfilling the Congressional mandate.

In contrast to the ground-based, optical LSST, space-based missions aim to detect NEOs using infrared cameras. The existing space-based mission, NEOWISE, is expected to continue until 2017, by which time it will have observed about 2,000 NEOs. The proposed next-generation space-based survey, Near-Earth Object Camera (NEOCam), would use a 0.5-metre telescope orbiting at the Sun–Earth L1 Lagrange point (about 0.01 AU from Earth towards the Sun). During a five-year baseline mission, it would aim to discover about two thirds of PHAs larger than 140 m. Another proposed space-based survey, Sentinel, would place a 0.5-metre telescope into an orbit similar to that of Venus. Sentinel is anticipated to be capable of detecting 90 per cent of NEOs larger than 140 m in about seven to 10 years of operation.

The thermal infrared emission from asteroids is better detected from space than from the ground, and can provide a more direct estimation of asteroid size. Depending on the orbit chosen, space-based telescopes can detect NEOs on orbits interior to the Earth more efficiently than ground-based telescopes. In practice, space-based infrared surveys and ground-based optical surveys are very complementary. By obtaining infrared plus visible light measurements, the size and albedo of the NEOs can be more accurately determined and more information about the physical properties of the NEO can be gathered. In addition, ground-based surveys are well suited for obtaining long-term observations of NEOs in order to very accurately determine their orbits.

**Treasure trove**

LSST is currently by far the most ambitious, multi-purpose, proposed survey of the sky. It will be a large, wide-field, ground-based imaging system designed to obtain multiple images per night, covering the sky visible from Cerro Pachón in northern Chile. The LSST design is driven by four main science themes: probing dark energy and dark matter; taking an inventory of the solar system; exploring the transient optical sky; and mapping the Milky Way.

The telescope will have an 8.4-metre primary mirror, an unusually large field of view (10 square degrees, or about 50 times larger than full Moon) and a 3,200 megapixel camera. LSST is a public–private project, with the US National Science Foundation supporting the telescope and site facility construction, data management system,
education and public outreach components, and
with the Department of Energy supporting the
camera fabrication. The construction of LSST will
be completed by the end of this decade, followed
by 10 years of operations.

For the theme of taking an inventory of the
solar system, the goal is to better understand the
process of planet formation and evolution, and the
relationship between our solar system and other
planetary systems. However, in the process of
cataloguing and characterising about five million
small bodies throughout our solar system, LSST
will also play a major role in PHA impact hazard
assessment and discovering NEO potential targets
for spacecraft missions. Simulations show that
LSST will be capable of measuring orbits for 80
per cent of PHAs larger than 140m after 10 years
of operations. In addition, the completeness can
be boosted to 90 per cent, with a negligible effect
on other science goals, by extending the planned
baseline survey by two years.

LSST is the only upcoming ground-based survey
capable of reaching this completeness level due
to its very large field of view. It will detect objects
as small as 10m at distances as large as 0.1 AU (15
million km, or about 40 times the Earth–Moon
distance) as well as 100–metre objects in orbits
similar to that of Venus. In addition, observations
will be also obtained at low solar elongations
to improve the completeness for objects within
Earth’s orbit. While such observations are less
efficient due to the increased thickness of Earth’s
atmosphere close to the horizon, LSST will still be
remarkably sensitive.

The LSST survey will open a movie-like window
on objects that change brightness, or move, on
timescales ranging from 10 seconds to 10 years.
The survey will have a raw data rate of about 15 TB
per night, and will collect over 50,000 TB of data
over its lifetime. The result will be an incredibly
rich and extensive public archive, a treasure trove
for breakthroughs in many areas of astronomy
and physics. About 20 billion galaxies and a similar
number of stars will be detected. For the first
time in history, the number of catalogued celestial
objects will exceed the number of living people!

LSST and its unprecedented science-ready
database, with about 30 trillion time-resolved
observations for 40 billion celestial sources,
will significantly contribute to the worldwide
democratisation of science. LSST will be in some
sense an internet telescope: the ultimate network
peripheral device to explore the universe, and a
shared resource for all humanity.