Asteroid surveys are the backbone of asteroid science, and with this in mind we begin with a broad review of the impact of asteroid surveys on our field. We then provide a brief history of asteroid discoveries so as to place contemporary and future surveys in perspective. Surveys in the United States have discovered the vast majority of the asteroids and this dominance has been consolidated since the publication of Asteroids III. Our descriptions of the asteroid surveys that have been operational since that time are focussed upon those that have contributed the vast majority of asteroid observations and discoveries. We also provide some insight into upcoming next-generation surveys that are sure to alter our understanding of the small bodies in the inner solar system and provide evidence to untangle their complicated dynamical and physical histories. The Minor Planet Center, the nerve center of the asteroid discovery effort, has improved its operations significantly in the past decade so that it can manage the increasing discovery rate, and ensure that it is well-placed to handle the data rates expected in the next decade. We also consider the difficulties associated with astrometric follow-up of newly identified objects. It seems clear that both of these efforts must operate in new modes in order to keep pace with expected discovery rates of next-generation ground- and space-based surveys.

1. INTRODUCTION

Without asteroid surveys there would be no asteroid science. The cumulative efforts of over 200 years of asteroid surveying has resulted in the discovery of over half a million asteroids in the inner solar system that range from just a tenth of an astronomical unit from the Sun to beyond Jupiter’s orbit. The surveys have identified asteroids that are the targets of spacecraft missions, that are the remnants of larger asteroids that were catastrophically disrupted long ago, and that allow us to untangle the complicated processes that formed our solar system billions of years ago. The surveys’ capabilities have improved over the decades as they took advantage of every new available technology to push their performance in area coverage, limiting magnitude, and data rates. Their efforts have enabled our community to advance our understanding of the past, current and future interactions of both the small and large objects in our solar system. This chapter provides a historical perspective on asteroid surveys, then focuses on their current capabilities and discoveries since Asteroids III, discusses the importance of targeted astrometric follow-up for critical objects, and concludes with a speculative forecast on how the next decade of asteroid surveying will unfold.

The benefits of a database containing a large number of asteroid orbit elements and basic physical properties have mostly been achieved over the past couple decades as a result of the NASA-funded near-Earth object (NEO) surveys. They attempt to optimize their surveying for the discovery of unknown NEOs but, in the process, discover and recover known asteroids throughout the solar system. While it seems obvious that ‘more is better’ it is not necessarily straightforward to justify the argument for different asteroid populations — how many asteroids are necessary for science? Is a complete survey required or is a statistical sample sufficient?
The first decade of intensive asteroid surveying at the end of the last century was motivated by NASA’s goal of detecting NEOs that are larger than 1 km in diameter. The impact on Earth of one of those objects is expected to have global consequences and the set of about 1,000 NEOs of that size or larger was thought to incorporate 90% of the impact risk (e.g. Morrison, 1992; Harris, 2008). Thus, the surveys had a relatively well-defined goal that was motivated by planetary defense rather than science: identify most of the largest hazardous asteroids that could threaten Earth. Progress towards achieving that goal could be measured against the derived population size or by the rediscovery rate (e.g. Jedicke et al., 2003; Harris, 2007). It is possible that there remain undiscovered large objects on an impact trajectory with Earth, but the probability is small.

The last decade of asteroid discovery, roughly since Asteroids III, has mostly retired the risk of an unanticipated impact of a globally devastating asteroid (e.g. Harris, 2008; Mainzer et al., 2011b). Having achieved that goal, the surveys are now focusing upon detecting even smaller asteroids with the goal of discovering > 90% of the potentially hazardous objects (PHOs) larger than 140 m in diameter because they 1) represent the lower limit of those that can cause serious regional ground destruction and 2) contribute roughly 90% of the residual hazard to the Earth from unknown impactors. The discovery rate for objects of less than 140 m in diameter is currently about 400 per year so that Asteroids VII could be published before the goal is reached unless new technologies are brought to bear in the coming decades.

Thus, for PHOs, there are well-defined and clearly-motivated practical goals for discovering a specific number of objects but the situation is not so clear for other asteroid populations in the inner solar system. How many main belt asteroids are necessary? To what absolute magnitude should we strive to be complete for Jupiter’s Trojan asteroids? Without the NEO surveys driving the discovery of asteroids to fainter apparent magnitudes and smaller sizes we would not have discovered, for example, extremely young asteroid families that can be traced back in time to their collision origin (e.g. Nesvorny et al., 2006; Nesvorny et al., this volume), widely-separated asteroid pairs on nearly identical orbits that point to YORP spin-up and tidal disruptions of large asteroids (e.g. Vokrouhlický and Nesvorny, 2008; Walsh et al., this volume; Vokrouhlický et al., this volume), main belt comets that provide evidence of a water reservoir that may have allowed life to thrive on Earth (e.g. Hsieh and Jewitt, 2006; Jewitt, 2012; Jewitt et al., this volume), and contemporary catastrophic disruptions of main belt asteroids that suggest that YORP driven rotational spin-up might be the dominant cause of their breakup (e.g. Jewitt et al., 2010; Denneau et al., 2015). In addition, we would not have been able to measure the ages of main belt asteroid families through fitting the characteristic Yarkovsky/YORP-induced ‘V’ shape of the families’ absolute magnitude vs. proper semi-major axes distributions (e.g. Vokrouhlický et al., 2006; Vokrouhlický et al., this volume) to constrain the dynamical and collisional evolution of the main belt since its formation (e.g. O’Brien and Greenberg, 2005; Morbidelli et al., this volume; Bottke et al., this volume).

The surveys’ capabilities are now so synoptic that most slow moving objects brighter than about V = 21 are routinely detected multiple times in a lunation, and will be re-detected regularly in the future, so that they require no specific allocation of resources for targeted follow-up observations. Indeed 80% of the known main belt asteroids with H < 16.5 are now numbered, meaning that their orbits are good enough to predict their future ephemerides to within 2" for at least the next decade. On the other hand, rapidly moving, nearby NEOs that may pose an Earth impact hazard in the future usually require rapid follow-up to measure their astrometric positions (Ticha et al., 2002) over as long an arc as possible during their discovery opposition to 1) accurately assess their Earth impact hazard (e.g. Milani et al., 2005; Harris et al., this volume) and 2) increase the probability that detections of the object in future apparitions can be associated with the discovery apparition observations (e.g. Milani et al., 2012; Farnocchia et al., this volume).

We think that continued asteroid survey efforts in the next decades are justified in order to expand upon the rich asteroid science yield of the past decades, to provide exciting new discoveries that will generate unexpected insights into our solar system’s formation and continuing evolution, and to further reduce the NEO impact hazard risk. The remainder of this chapter provides an introduction to the history of asteroid surveys before Asteroids III, the continuing survey improvements and their current status as of publication of Asteroids IV, the importance and state-of-the-art of follow-up efforts, and our perspective on upcoming surveys and technologies as we look forward to Asteroids V.

2. A BRIEF HISTORY OF ASTEROID DISCOVERY (PRIOR TO ASTEROIDS III)

The first asteroid to be discovered, (1) Ceres, was visually identified by Father Giuseppe Piazzi, director of the Palermo Observatory, on the morning of 1801 January 1, the first day of the nineteenth century. Piazzi was identifying and correcting the positions of stars in an existing catalog when he noticed that one ‘star’ in Taurus shifted position from night to night. He followed the object until 1801 February 11 but his discovery was not announced until the summer of that year. It was recovered on 1801 December 7 only after Karl Gauss, with characteristic genius, provided an elliptic orbit for (1) Ceres that allowed an accurate-enough ephemeris prediction. Three more asteroids were discovered shortly thereafter: Heinrich Olbers identified the second and fourth asteroids, (2) Pallas and (4) Vesta, in 1802 and 1807 respectively while Karl Harding discovered (3) Juno in 1804. It was another 41 years until (5) Astraea was discovered in 1845, and the discovery rate would remain less than about one per month till about
the time of the advent of astrophotography. There were only ten known asteroids by mid-century and 447 by 1900 (see Figure[1]).

The era of photographic asteroid discovery began in 1891 when Max Wolf compared the images on three successive photographic plates to detect the motion of (323) Brucia, the first of Wolf’s 321 asteroid discoveries. Trailed detections of asteroids on single long-exposure photographic plates were also used to identify asteroids and Gustav Witt discovered the trailed image of the first near-Earth object, (433) Eros, at the Urania Observatory in Berlin in 1898.

The pioneering photographic asteroid surveys in the 1970s and early 1980s marked the beginning of the modern NEO discovery era (see Figure[1]). Gene Shoemaker and Eleanor Helin began using the 18-inch Palomar Schmidt telescope in southern California, USA, for finding NEOs in 1973 and were joined by Carolyn Shoemaker in the early 1980s (Helin and Shoemaker, 1979). Their early photographic surveys identified asteroids using manually operated blink comparators and stereomicroscopes that enabled visual comparison of images of the same portion of sky taken several minutes apart. The vast majority of the objects in the images were stationary stars and galaxies but a moving NEO would be in a slightly different position on each photograph so that it would appear to jump back and forth when each image was quickly viewed in turn with the blink comparator. Alternately, the NEO’s image would appear to ‘float’ above the background stars when two different images were examined at the same time with a stereomicroscope. (For more details concerning these pioneering NEO search efforts see; e.g. Cunningham, 1988; Stokes et al., 2002; Yeomans, 2013)

The surveys entered the modern era in 1984 when the Spacewatch telescope (see §3.1) became the first survey to employ a camera with a charge-coupled device (CCD) focal plane (see Figure[1]). Their first $320 \times 512$ pixel CCD detector was replaced in 1989 with a large format $2048 \times 2048$ CCD that was used for three years until they obtained a high-efficiency ($\sim 70\%$) thinned $2048 \times 2048$ CCD. The system was operated for about 23 nights per month with the CCD read out in a time-efficient ‘drift-scanning’ mode in which the right ascension axis was stationary so that the star field would drift through the telescope’s field-of-view (FOV) while the CCD detector was read out at the same rate. This technique allowed the survey to image about 200 deg$^2$ each month to a limiting $V$-band magnitude of $\gtrsim 21$. Each scan was repeated three times with about thirty minutes separation and automated software identified moving objects in the field (Rabinowitz, 1991).

The NEO discovery rate increased dramatically in the late 1990s (see Figure[1]) when NASA increased the funding available for NEO surveys, partly in response to impact awareness generated by the 1994 impact of Comet Shoemaker-Levy 9 with the planet Jupiter. The perfect storm of increased funding coupled with the decreasing cost of CCDs and the availability of frame-transfer CCDs enabled the rise of the LINEAR (§3.3) and Catalina (§3.3) NEO surveys that dominated the modern survey era for about two decades leading up to and through Asteroids III. (Stokes et al. (2002) provides more details of the history and state of asteroid surveys leading up to Asteroids III.)

3. ASTEROID SURVEYS (since Asteroids III)

All contemporary asteroid surveys use extremely efficient CCDs to record digital images of the sky. While CCD detectors are far more sensitive and accurate than film their application to asteroid discovery is similar. Three or more CCD images are taken of the same region of the sky with successive images separated in time by about 30 minutes. The images are then compared in software to identify detections that have systematically moved to different positions from one image to the next. The rate of motion of the detections from one image to the next, the direction they appear to be traveling, and their apparent brightness are helpful in identifying interesting objects and can provide first-order estimates of an object’s distance from Earth, its size and general orbital characteristics. For example, an object that appears to be moving very rapidly from one image to the next ($> 1$ deg/day) is almost certainly an NEO. New NEO discoveries are usually still verified with the human eye even though sophisticated and automated software analyses of the CCD images have replaced manual identification of moving objects.

In 1998, NASA established the goal of discovering 90% of NEOs larger than one kilometer in diameter and in 2005 Congress extended that goal to include 90% of the NEOs larger than 140 meters (George E. Brown, Jr. Near-Earth Object Survey Act). There are thought to be about 1,000 near-Earth objects larger than one kilometer diameter and roughly 26,000 larger than 140 meters (e.g. Granvik et al. (2015); Harris et al., this volume). The desire to meet the NEO goals has enabled the funding and driven the success of the asteroid surveys over nearly the past two decades.

Asteroid surveys that search the largest volume of sky each month will discover the most NEOs (Bowell and Muinonen, 1994), all other things being equal. How much sky each telescope survey depends upon several factors including the number of clear nights available for observing, the telescope aperture and FOV, and the sensitivity and efficiency of the CCD detector. That being said, not all regions of the sky are equally productive for discovering new NEOs (e.g. Bowell and Muinonen, 1994; Chesley and Spahr, 2004; Vereš et al., 2009). Once the most effective regions are fully surveyed it is important to extend the search to greater distances from Earth or, in other words, to fainter limiting magnitudes.

Space-based asteroid surveys have advantages over ground-based observing in that they are not hindered by weather, they can search continuously, can observe in the infrared where asteroids are brighter and there are fewer background sources, and space telescopes can observe NEOs when they are much closer to the Sun (Mainzer et al.,
A case in point is the ∼ 18 m diameter asteroid that injured more than 1,500 people when it airburst over Chelyabinsk, Russia, on 2013 February 15 that was not detected by ground-based surveys since it came from a sunward direction (e.g. Brown et al., 2013). Of course, space-based surveys are expensive, risky, can be data-rate limited due to the availability and limitations of the downlink from the spacecraft to the ground, and they are not repairable in the event of a major failure.

The asteroid surveys have discovered about 90% of the NEOs larger than 1 km diameter since NASA’s initiation of its NEO Observations (NEOO) program in 1998 (Mainzer et al., 2011b), and a good fraction of those larger than 140 m. Progress toward meeting the goals can be monitored on the NEO discovery statistics page at neo.jpl.nasa.gov/stats/. The vast majority of those NEO discoveries were made by NASA-supported ground-based telescopic surveys (see table 3) and in the following sub-sections we briefly describe the major surveys that were or are operational since Asteroids III in roughly chronological order by start date (JPL maintains a list of NASA-supported NEO survey programs at http://neo.jpl.nasa.gov/programs/).

3.1 Spacewatch (1983-present)

The Spacewatch team was a pioneer in digital detection of NEOs (e.g. Rabinowitz, 1991). They discovered the first NEO on digital images in 1989 and reported the first automated (software) discovery in 1990. They led the effort to automate the discovery and follow-up of NEOs, culminating in the modernization of their 0.9 m and 1.8 m telescopes that can both be operated from a single control room by a single observer.

They began using their custom-built 1.8 m aperture telescope for NEO surveying and follow-up in 2002. Later that same year their 0.9 m was instrumented with a large-scale mosaic camera consisting of four 4608 × 2048 CCDs to take advantage of its new optical system that provides a 2.9 deg² FOV. The 0.9 m telescope’s new optical configuration required that it operate in the conventional ‘stare’ mode whereas the 1.8 m telescope continued to be operated in the ‘drift-scan’ mode until 2011. From 2005 through 2008 Spacewatch gradually shifted its emphasis from NEO surveying to follow-up as other surveys began to dominate their NEO follow-up rate by more than 50% while at the same time halving the astrometric residuals. The Spacewatch 1.8 m telescope is currently among the world’s leaders in faint-object follow-up, especially in terms of critical follow-up of the most challenging faint objects.

3.2 Near-Earth Asteroid Tracking (NEAT, 1995-2007)

Beginning in 1995 the JPL Near-Earth Asteroid Tracking program (NEAT, Pravdo et al., 1999) operated survey telescopes on the summit of Haleakala, HI, USA, in cooperation with the Air Force. The GEODSS 1 m telescope was equipped with a 4k×4k CCD and initially utilized 12 nights per month centered on new moon (1995 December to 1996 December) subsequently reduced to 6 nights per month (1997 January to 1999 February). In 2001 February NEAT began using a modified 1.2 m telescope, part of the U.S. Air Force Space Surveillance System on Maui, HI, USA. Nightly pointing lists were generated at JPL for the telescope control computer in Maui and small sub-images of candidate NEOs were transferred back to JPL for inspection by JPL scientists. In 2001 the NEAT program transitioned to the 1.2 m Schmidt telescope at Palomar Mountain in southern California, USA, before ceasing operations in 2007.

3.3 Lowell Observatory NEO Survey (LONEOS, 1993-2008)

The Lowell Observatory NEO Survey (LONEOS; Bowell et al., 1995) operated from 1993 through 2008 using the Lowell Observatory 0.6 m Schmidt telescope at Anderson Mesa near Flagstaff, AZ, USA. The relatively small aperture telescope was competitive because it had a large FOV of about 8 deg² instrumented with two 2k×4k cooled CCDs. LONEOS collected four 45 s exposures of each field that were automatically searched for moving objects down to V ~ 19.3. The LONEOS system’s productivity eventually declined due to competition with larger aperture survey telescopes so they switched their primary objective to photometric observations of NEOs and finally ceased operations in 2008.

3.4 Lincoln Near-Earth Asteroid Research program (LINEAR, 1996-2013)

The LINEAR survey (Stokes et al., 2000) was operated out of Socorro, NM, USA, by the MIT-Lincoln Laboratory team that was based in Lexington, MA, USA. The legacy 1 m LINEAR telescope system is located at Lincoln Laboratory’s Experimental Test Site near Stallion Range Center on the US Army’s White Sand Missile Range in central New Mexico, USA. It began operations in early 1996 but was in routine use from 1998 March through 2013 May. The survey used two 1 m aperture telescopes originally designed as prototypes for Earth-orbiting debris tracking. LINEAR’s success was driven by the application of electro-optical sensor technology, originally developed for US Air Force Space Surveillance, to the problem of discovering near-Earth asteroids and comets. Their frame-transfer CCDs allowed large areas of sky to be surveyed extremely efficiently because the camera required effectively zero readout time. Furthermore, the rapid-readout CCDs and access to fast-computing resources allowed them to apply an advanced image processing technique involving generating a median of 5 images of the same field and subtracting the median from the sum of the same 5 images to generate difference images that contained only transients and relatively few artifacts. The differenced images were then...
searched for transient detections moving in roughly straight lines (tracklets). During the late 1990s and early 2000s they could survey several thousand square degrees per night to $V \sim 19$ enabling the program to singlehandedly discover more than a third of all NEOs one kilometer in diameter or larger. Lincoln Laboratory discontinued use of the 1 m system in 2013 while it transitions to the use of the 3.5 m Space Surveillance Telescope (SST, see §7.2).

3.5 Catalina Sky Survey (CSS, 1992-present)

The University of Arizona’s Catalina Sky Survey (CSS, Larson et al., 1998) has been the primary NEO discovery system over much of the time since Asteroids III and has done so while remaining cost-competitive. Their success can be traced to remaining focussed on their primary objective of discovering NEOs; employing dedicated, professional, skillful observers; and by standardizing equipment and software across their different sites. For instance, all the cameras at their three sites are identical, thinned, 4k×4k back-illuminated detectors packaged by Spectral Instruments, Inc., of Tucson, AZ, USA, that are cooled with a closed-cycle cryocooler. The use of identical cameras has minimized hardware and software development, maintenance and operations costs. Their dedication to continual improvement, comprehensive sky coverage, human vetting of candidate discoveries, and on-site recovery capability have further contributed to their success over the last decade.

The CSS was preceded by the Bigelow Sky Survey (BSS) that photographically searched for new asteroids and comets between 1992 and 1996 (Spahr et al., 1993; Spahr et al., 1996). The experience gained in operating the BSS informed and motivated modifications to the telescope, camera and software beginning in 1997 so that the CSS’s CCD survey began producing observations in 1998.

The CSS has used three different telescopes in the past ten years and in 2013 alone discovered 603 NEOs, easily making it the top survey program that year. Their two primary telescopes are the Catalina Schmidt (703) and the Mt. Lemmon telescopes (G96) but their third site, the Siding Spring Schmidt (E12) in Australia, has delivered enough NEOs to place it in the top 6 NEO discovery sites in each of the past 10 years. About 20% of CSS observing time is devoted to post-discovery follow-up observations (see §5).

The Catalina Schmidt (703) in the mountains north of Tucson, AZ, USA, was upgraded to a f/1.8, 0.7 m telescope from 2003 to 2004 which increased their sensitivity to $V \sim 20.0$. Its 8.2 deg$^2$ FOV enabled the site to survey 1,000 to 1,500 deg$^2$ per night and vaulted the CSS program into the lead in terms of annual discoveries.

In 2004-2005 the CSS team procured a 4k×4k CCD and then built and installed a prime-focus camera that delivers a 1.2 deg$^2$ FOV on their Mount Lemmon 1.5 m telescope (G96). Its limiting magnitude reaches $V \sim 21.5$ under good conditions and they can survey $\sim 200$ deg$^2$ on an average night. This survey excels at finding very small objects that are very close to Earth (Jedicke et al., 2014) and demonstrates the need to shift to larger optical systems in order to complete the inventory of smaller, yet still threatening, NEOs. e.g. The CSS identified the only two Earth impactors that were discovered in advance of impact (2008 TC$_3$, Kowalski et al., 2008; 2014 AA, Kowalski et al., 2014).

The 0.5 m Uppsala Schmidt telescope (E12) at Siding Spring, Australia, was operated by the CSS for several years when it was the only NEO survey in the southern hemisphere. However, in 2013 the Australian dollar became much stronger relative to the U.S. dollar-based funding from the NASA NEOO program compared to when the survey was established. The combination of the exchange rate shift and the telescope’s modest aperture and FOV reduced the cost-effectiveness of the survey compared to the CSS’s northern hemisphere assets and the decision was made to end support for this facility.

3.6 Panoramic Survey Telescope and Rapid Response System (Pan-STARRS, 2010-present)

The 1.8 m Pan-STARRS1 (PS1; Wainscoat et al., 2013) telescope on Haleakala, HI, USA, was developed by the University of Hawaii’s Institute for Astronomy and operated by the PS1 Science Consortium (PS1SC) until early 2014. It was the prototype telescope for the 4-telescope Pan-STARRS system (Kaiser et al., 2002) that was supposed to be operational late in the last decade but may never be completed. The PS1 CCD camera was the largest in the world when it was originally built, with a focal plane consisting of an almost complete 8 × 8 array of CCDs (the four corner CCDs were left out of the focal plane) with a total of about 1.4 gigapixels. The large focal plane combined with the system’s f/4 optics yields a $\sim 7$ deg$^2$ FOV that has moved PS1 to be the leading PHO discovery site beginning in calendar year 2012. In 2014 it will discover about 4× more PHOs than the second most successful site.

The first PS1 NEO discoveries were recorded in the second half of 2010 but only about 5% of the observing time was devoted to NEO discoveries at that time. The NEO survey time fraction was increased to 11% beginning in 2012 November. In addition, 56% of the observing time was used for a ‘3π’ sky survey in three filters that was also executed in a manner that led to the discovery of NEOs. The time devoted to the NEO search was increased to 100% beginning in 2014 April with funding provided by NASA’s NEOO program after the end of the PS1 Science Consortium.

PS1’s strength lies in having the faintest magnitude limit of any active NEO survey, reaching $V \sim 22$ under good conditions. This allows the team to discover NEOs that are too faint to be detected by the other systems. Their excellent site in the middle of the Pacific Ocean allows PS1 to survey the ‘sweet spots’ near the Sun where the sky-plane PHO density is highest if the system can reach fainter than $V \sim 21$ (Chesley and Spahr, 2004, Vereš et al., 2009).

PS1 developed a sophisticated image processing pipeline (IPP, Magnier, 2006) that feeds transient detections to the Moving Object Processing System (MOPS, Denneau
et al., 2013), that uses kd-trees to quickly link transient detections into tracklets (Kubica et al., 2007). The final observations are extremely accurate with astrometry good to $\lesssim 0.1''$ (Milani, 2012) that allows the MPC to tightly constrain NEO orbital solutions and uncertainty maps to facilitate the recovery of PS1 NEO candidates.

3.7 NEO Wide-field Infrared Survey Explorer (NEOWISE, 2010-present)

The NEOWISE program (e.g. Mainzer et al., 2011a; Mainzer et al., this volume) observes and discovers NEOs and other asteroids in the near-IR with the 0.4 m telescope aboard the Wide-field Infrared Survey Explorer (WISE) spacecraft (e.g. Cutri et al., 2012; Wright et al., 2010). The spacecraft was launched on 2009 December 14 into a ‘sun-synchronous’ polar orbit around Earth (the spacecraft’s orbital plane is always roughly perpendicular to the Earth-Sun line) and as it orbited it continuously surveyed a 47° wide strip of sky in the opposite direction from Earth. WISE operated for ten months in 2010 performing an all-sky astronomical survey in four bands centered at 3.4, 4.6, 12 and 22 $\mu$m. When the hydrogen coolant for the two longest wavelength detectors was exhausted, a secondary post-cryogenic mission continued for four more months using just the two shorter wavelength detectors, and then the spacecraft was decommissioned and hibernated on 2011 February 17. After more than two and a half years the spacecraft was awakened from hibernation and NEOWISE was reactivated in 2013 September for a planned 3 year observing period using just the 3.4 $\mu$m and 4.6 $\mu$m passbands (Mainzer, 2014). Its first NEO discovery in the new operational phase, 2013 YP$_{1,39}$, occurred on 2013 December 29.

NEOWISE’s Sun-synchronous survey mode imposes a time limit of about 36 hours during which images at a specific location can be acquired. Hence, the program requires ground-based NEO candidate follow-up by a dedicated network of amateur and professional astronomers to secure their orbits (see [5]). NEOWISE also detected tens of thousands of known asteroids in the IR that allowed diameter measurements of thousands of objects thus enabling a range of studies of the origins and evolution of the small bodies in our solar system (e.g. NEO, Mainzer et al., 2011b; MBO, Masiero et al., 2014; Jupiter Trojans, Grav et al., 2012; and Mainzer et al., this volume).

3.8 Other Contributions

Amateur astronomers have historically played a role in advancing the astronomical fields but their contribution to NEO discovery has been limited due to their access to telescopes of relatively modest apertures. From 1998 through 2013 only about 1.8% of the 10,044 discovered NEOs were found by the amateur community. The most productive team was the Las Sagra Survey (LSS) operated in Spain by J. Nomen, R. Stoss, and others. They discovered 79 NEOs prior to being funded professionally by the European Space Agency for space debris tracking. During the same time period only 99 other NEOs were discovered by amateurs from the rest of the world combined.

A small number of asteroids are discovered serendipitously by professional observers or other astronomical surveys in the course of their work that is not always primarily associated with asteroids. For instance, the International Scientific Optical Network (ISON; Molotov, 2010) is designed to identify and track Earth-orbiting space-debris but it’s capabilities naturally serve the asteroid identification processes illustrated by their discovery of the spectacular Comet ISON (C/2012 S1). Similarly, the Palomar Transient Factory (PTF; e.g. Polishook & Ofek, 2011) is an all-sky astronomical survey designed to identify transient and variable objects that has also identified many asteroids and NEOs.

4. THE MINOR PLANET CENTER (MPC)

All the candidate detections of minor planets identified by the surveys are delivered to the Minor Planet Center (MPC, http://minorplanetcenter.net) — the IAU’s official international repository and distributor of asteroid astrometric observations, minor planet orbits, and identifications. The MPC’s goal is to identify and/or link all reported minor planet observations in nearly real time. This is a challenging process because the MPC has experienced a 7× increase in reported observations over the time since Asteroids III (see Figure [1]) and the time required for orbit determination and linking increases faster-than-linearly with the number of observations in the database. Fortunately, Moore’s Law and the implementation of improved operational procedures have allowed the MPC to handle the increased data and analysis rate. Today, the MPC can automatically and seamlessly receive and process a few million observations of a few hundred thousand minor planets each day from both ground- and space-based observatories.

The MPC concentrates on expeditiously processing NEO discoveries and observations because they are of interest to NASA and the public. Ephemerides need to be provided promptly so that follow-up telescope facilities can quickly recover the objects. The MPC checks all reported NEO candidate ‘tracklets’ (sets of detections that are claimed to be of the same object) for identification with known objects, computes the likelihood that unknown objects are new NEOs, and posts the best candidates on the NEO Confirmation Page (NEOCP) for follow-up (the NEOCP is available at http://www.minorplanetcenter.net/iau/NEO/ToConfirm.html). The follow-up efforts are described in [5]. The ESA’s NEO Coordination Centre also maintains a parallel and prioritized follow-up list at http://neo.ssa.esa.int/web/guest/prioritylist.

The NEOCP was handily validated in 2008 October when the MPC identified a CSS discovery that would impact Earth only 20 hours after discovery (Kowalski and Chesley, 2008). The international network of observers monitoring the NEOCP quickly responded (see [5]) and reported more than 800 astrometric observations, multiple light curves and even a spectrum, over a timespan of less
than a day. As a result of this coverage JPL predicted that the object now known as 2008 TC$_3$ would impact in a small desert area in northern Sudan. This prediction was subsequently confirmed by visual and satellite reports and with the collection of meteorite fragments on the ground (e.g. Jenniskens et al., 2009; Jenniskens et al., this volume).

The MPC’s database (see table 2) mostly contains optical observations of main belt asteroids even though much of the MPC’s time and effort is devoted to dealing with NEOs. As of this writing there are almost 400,000 minor planets classified as ‘numbered’ (most of them in the main belt), meaning that their orbits are of sufficient accuracy that their ephemeris uncertainties in the next decade are no more than a few arc-seconds. To be numbered an object usually needs to be observed over a period of at least 4 oppositions with detections on more than 1 night in most of the apparitions. This rule-of-thumb applies to main belt objects that typically have only optical sky-plane positions — NEOs may have secure orbits with just two apparitions of data because of the power of parallax for nearby objects to reduce the uncertainty on the orbit elements. Similarly, the range and range-rate accuracy available with radar may be combined with optical observations from just a single apparition to yield good orbits (e.g. Ostro et al., 2004). In total, the numbered objects have increased by more than a factor of 10 since Asteroids III and about 90% of those objects were discovered by just ten surveys or sites (see table 3). Many of the objects that are now numbered were discovered more than a decade ago, before Asteroids III, because it requires about 10 years before a typical main belt object has been detected in enough apparitions to allow it to be numbered. Thus, the tremendous number of new discoveries by contemporary NEO surveys (see §3) will only be numbered as this decade progresses towards the publication of Asteroids V.

The unfortunate reality of the difference between the capabilities of professional and amateur facilities is that only 0.6% of the numbered objects in the top 10 list were contributed by amateur observatories. Eight of the top ten most productive programs are, or were, funded directly by NASA specifically for discovery or follow-up of NEOs. Thus, it is clear that the discovery of minor planets is almost uniquely a NASA-funded survey effort based in the United States. Indeed, fully 80% of the discoveries were realized at just a handful of NASA-funded NEO search programs led by the LINEAR program (see §3.4).

The MPC database contains observations and orbits of objects that were detected in multiple oppositions, a single opposition, and even on only two nights. The sum total of all these objects is currently comparable to the number of numbered objects (see table 2). The accuracy of the ephemerides for each successive class of objects decreases dramatically such that single opposition orbits might be suitable for predicting the location of the object for only another 1 or 2 years while objects observed on only 2 nights can typically only be used for about 10 days.

Finally, the MPC maintains a publicly available file of all single-night detections that currently cannot be linked or identified with other minor planets. This pejoratively dubbed (by Brian Marsden in the mid 1990s) ‘One Night Stand’ (ONS) file now contains over 8 million observations. While it is likely that many of the observations in this file represent duplicates, false detections, and errors, it is also likely that the file includes several hundred thousand uncatalogued minor planets. The MPC currently employs a graduate student (J. Myers, U. of Arizona) who is developing advanced linking techniques to extract as many objects as possible from the ONS file but it will always contain a high fraction of unlinkable and likely false detections.

One challenge at the MPC is linking and processing data sets of very different observational quality. For example, the mean astrometric residual for observations prior to the CCD era (c. 1995) is about 1-2″ while residuals from the modern Pan-STARRS program (§3.6) are ∼ 0.1″ — a factor of 10 to 20 improvement! Even today, the mean residuals for survey data from the professional surveys ranges from about 0.05″ to 0.7″.

5. ASTROMETRIC FOLLOW-UP, RECOVERY AND PRECOVERY

Modern survey telescopes are specifically designed to have a wide FOV and rapid readout in order to image as much sky as possible so that using them for targeted follow-up of specific objects is an inefficient use of their capabilities. Instead, the surveys identify and report likely asteroid tracklets to the MPC on a nearly real-time or nightly basis and then continue to survey the sky for other candidates. They rely on other ‘follow-up’ facilities to obtain more observations of the objects for verification and to secure their orbits. Follow-up usually refers to obtaining astrometric and photometric observations of an object to secure its orbit and determine its absolute magnitude but may also include various types of ‘physical characterization’ including obtaining an object’s light curve to determine its rotation rate and, perhaps, shape, or spectra to determine its taxonomy (and mineralogy). This chapter and sub-section will concern itself almost exclusively with astrometric follow-up.

The most challenging follow-up is for the NEOs. More distant objects tend to move slowly so that their ephemeris uncertainties are relatively small and, in any event, they will be re-detected in the course of normal ongoing survey operations. The first detections of a new candidate NEO typically span a temporal arc of less than an hour and represent just the beginning of the lengthy and complex discovery process. First, the candidate must be confirmed as being a real and unknown object — it is not uncommon for reported candidates to be false because of processing errors such as mis-linking of two different asteroids or combining false detections in an image into a false tracklet. Once an object is established as being real and recoverable, discovery observations must be followed by an observational campaign to establish the object’s orbit with enough accuracy to enable it to be ‘recovered’ in the future. (Recovery is the
process of obtaining new observations that can be attributed to an object.) The extension of the observed arc is essential for more accurate orbit determination that leads to a better understanding of the object’s dynamics either because of its scientific interest or because of its possible impact threat to Earth (e.g. Milani et al., 2000). Some candidate NEOs may be real but moving so fast that they are effectively unrecoverable due to timing considerations, weather, and/or ephemeris uncertainties. The most critical follow-up takes place within about three days of discovery because the initial observations are usually insufficient to even broadly identify the orbital properties of the new object. This is because a small number of observations by a single observatory over a short timespan do not contain enough information to determine the geocentric distance of the object — they contain very little parallax information and, as a result, ephemerides rapidly become extremely uncertain or useless. Obtaining follow-up observations of an asteroid is so essential that only those with confirmatory observations are eligible for official designation and assignment of discovery credit by the MPC.

An illustration of the need for rapid follow-up is asteroid 2014 JR$_{24}$ that was discovered at magnitude $V \sim 17.2$ on 2014 May 6 by the CSS. Its diameter is in the 4 to 8 m range (based on its absolute magnitude, $H = 29.3$) and it made a close approach to Earth of about 0.3 lunar distances on 2014 May 7 when it reached a peak magnitude of $V \sim 15.6$. Though some astrometric follow-up was obtained there was no physical characterization of this interesting close flyby and potential radar target, and its apparent magnitude dropped to $V \sim 27$ within three days of discovery thereby eliminating the opportunity for further follow-up. It will not have a favorable apparition for more than a decade at which time the recovery will necessarily be serendipitous because the ephemeris uncertainty will be large.

There are a variety of assets for follow-up of recently discovered asteroids ranging from self-funded, highly-productive, sub-meter class telescopes (e.g. Birthwhistle, 2009), to NASA-funded 1-2 meter class telescopes and, increasingly common, even access to ‘big glass’ in the 4 to 8 m range (Abell, 2013) for characterization studies (table 4). FOVs for the facilities extend from arc-minute scales to about a degree; bigger fields facilitate astrometric follow-up when ephemeris uncertainties are large. The Astronomical Research Observatory (ARO) located in Westfield, IL, USA, currently tops the NEO follow-up list while at the same time contributing to astronomical education and public outreach by involving amateur astronomers and students. They have recently included a southern hemisphere site at Cerro ‘Tololo, Chile, to follow-up objects that are too far south for most of the follow-up facilities that are located in the northern hemisphere. Large aperture telescopes with faint limiting magnitudes that can gather good signal-to-noise detections even through thin clouds are valuable tools for faint objects or when weather conditions are less than optimal (e.g. Mauna Kea and Magdalena Ridge in table 4). Unfortunately, these large aperture observatories are typically only available for follow-up on a few nights per lunation because they are not dedicated NEO facilities. The researchers and sites within the University of Hawaii network (Tholen et al., 2013, Wainscoat et al., 2013) give preference to follow-up of NEO candidates discovered with the PS1 telescope using their 2 m class and larger telescopes on Mauna Kea, a big advantage for follow-up of the smaller/fainter objects being discovered by PS1. The Magdalena Ridge Observatory’s fast-tracking 2.4 m telescope (MRO; Ryan et al, 2002) located in New Mexico, USA, has the ability to accurately track rapidly moving targets that is essential for follow-up of challenging faint objects or for physical characterization (i.e. to keep the moving object on the spectrograph’s slit). MRO performs follow-up astrometry and real-time characterization (spin rates and composition), achieves sub-arcsec point spread functions (PSFs) even close to the horizon (pushing the limits to lower declinations than typical for the northern hemisphere), and can have multiple instruments mounted simultaneously (for rapid switching between photometry and spectroscopy).

It is common, natural, and unfortunate that a recently discovered object receives a lot of attention primarily during the few days after discovery when often hundreds of astrometric and physical observations are collected by professional and amateur observers. The attention is explicable because objects tend to be discovered near a maximum in apparent brightness so that all aspects of follow-up are easier. However, the major determinant in orbit element accuracy is the temporal coverage, not the number of observations. i.e. there is an opportunity cost of too many observations because most of them will not contribute to improving the orbit. It is therefore desirable that observers that have access to large aperture telescopes obtain astrometric measurements of the most important targets down to the limiting magnitude of their instrumentation (e.g. $V \sim 26$ for 8 to 10 m class telescopes such as that achieved in the ESA’s efforts with the Very Large Telescope (VLT; Micheli et al., 2014) and Large Binocular Telescope (LBT). Only this additional optical and orbital-arc coverage will make it possible to determine an orbit accurate enough to recover the object in its next apparition, that may be many years or even decades in the future, unless radar data are available (e.g. Ostro et al., 2004). The wasted effort and lack of temporal coverage for important objects suggest that there is a need in our community for an enhanced follow-up coordination effort beyond the current capability of the NEOCP. A centralized scheduling site that assigns available observing sites to specific targets based on weather, limiting magnitude, location, etc., could increase the efficiency of the overall follow-up effort (we note that this effort could be a component of the ‘Management Action’ called out by NASA’s Office of Inspector General’s report on the NEO effort; IG-14-030, 2014 Sept 15). The ESA NEO Coordination Centre is already coordinating follow-up observations of high-relevance targets by a worldwide network of cooperating observatories by providing them with rapid triggers.
when an observational opportunity arises appropriate for their systems. Over the past year their coordination efforts have contributed to the removal of 20 high-rated virtual impactors from their impact risk list.

The subsequent recovery of an object in a future apparition, that was enabled by a well-orchestrated follow-up effort in the discovery apparition, will result in a dramatic decrease in its orbit element uncertainty and correspondingly extend the ephemeris accuracy for decades into the future. However, in some (rare) cases an object’s dynamics may be so complex that, even then, predicting its motion is non-trivial. This often occurs when there are future close encounters with major planets or when non-gravitational forces become relevant. In these cases, observational coverage extending over multiple apparitions is often necessary to model the phenomena to a sufficient level of accuracy to accurately predict the object’s future behavior (e.g., Farnocchia et al., 2013; Chesley et al., 2014; Farnocchia et al., this volume).

The rationale for, and scientific benefits of, observations of asteroids at the Arecibo radar facility (Puerto Rico) and Goldstone Deep Space Network (California, USA) are unassailable but radar follow-up and characterization is expensive in time and resources. Radar directly and uniquely provides range, range-rate, shape, spin, and size data that complement the optically-derived physical information (e.g., Ostro & Giorgini, 2004) and enables computation of asteroid ephemerides much further into the future than ephemerides derived from optical-only astrometry because of radar’s exquisite precision in measuring the object’s range and range-rate. However, the only way that a radar facility can detect an object is with an accurate orbit provided by optical assets. Thus, radar is typically employed only for the most “interesting” objects.

The follow-up effort is more complicated for space-based discoveries (e.g., from NEOWISE: Mainzer et al., this volume). Delays in posting the candidate NEO’s ephemerides caused by scheduling the Deep Space Network for data transmission from the spacecraft (by several days) can result in untenable ephemeris errors. Furthermore, if an NEO has been discovered in a passband that is not a ground-based standard (e.g., an IR space telescope) then the transformation from the spacecraft’s passband to ground-based passbands can generate significant errors in the predicted apparent magnitudes. The apparent magnitude can be much fainter than expected if the object is of low-albedo (dark), such that acquiring good signal-to-noise detections for the object is difficult or impossible from the ground. Future wide or deep space-based surveys will need to carefully consider ground-based follow-up requirements or build self-follow-up into their survey strategy.

The future needs for asteroid follow-up and rapid physical characterization are clear — neither will keep pace with the expected discovery rates of future surveys (see §4). The mean $V$-magnitude of asteroids at discovery is now about 20, which limits follow-up and characterization sites to professional telescopes or a handful of the most advanced amateur astronomers. As the capabilities of the ground- and space-based survey telescopes continue to improve, pushing the mean discovery magnitude to even fainter values, the follow-up contribution from the amateur community will drop. This will require the survey telescopes to adopt self-follow-up survey strategies that re-acquire their own discoveries several times per month. Indeed, the advent of deep and wide surveys has changed the cost-benefit analysis of separating surveying and follow-up such that it may now simply be more efficient to do both with the same system in an integrated discovery & follow-up survey program. The re-observing strategy will reduce the possible discovery rate but the good news is that the strategy will extend the main belt minor planet catalog to much smaller sizes.

In many important cases it has been possible to dramatically increase the known arc-length for an object that has become unobservable by identifying ‘precovery’ observations in historical images. Over the last decade most professional observatories and surveys have developed online repositories of all their astronomical images, including digitizing very old photographic plates with associated astrometry and photometry of all sources in the images. Most of the images were acquired for projects unrelated to asteroids but some of them contain unrecognized detections of known asteroids. The most obvious example is the MPC’s one-night stand file (1) that is automatically searched by the MPC for precovers when feasible. In other cases, and increasingly more commonly, a survey’s archival detection database can provide precovery observations. Although the survey’s images were already inspected for moving objects there may be cases where an object was too faint to be detected or reported with confidence, but a precovery tracklet can be identified given a new object’s ephemeris. The success of the precovery efforts coupled with the relatively modest cost of archiving images suggest that surveys should ‘save all the bits’ i.e. every bit of every pixel of every image should be stored and, even better, searchable and accessible in an online repository.

6. POPULATION STATISTICS

We tend to think of distinct populations of asteroids in the inner solar system even though we know that they are actually inter-related. For instance, the NEOs are fragments created in the collisions of main belt asteroids that have been transported to near-Earth space by orbital evolution driven by gravitational dynamics and thermal recoil forces (e.g., Binzel et al., this volume). Furthermore, we are now beginning to understand that many main belt asteroids may be implanted objects that were originally formed elsewhere in the proto-solar system. Thus, in this section we attempt to address inner solar system asteroids holistically, providing orbit element distributions of NEOs, MBOs and Jupiter’s Trojans, on the same scales and figures and touch upon the transfer of objects between them.

That being said, we can not avoid the conventional nomenclature for the populations so that when we refer
to NEOs we explicitly mean those objects with perihelion $q \leq 1.3 \text{ au}$ and semi-major axis $a < 4.2 \text{ au}$. The MBOs are defined as those with $q > 1.3 \text{ au}$ and $a < 4.8 \text{ au}$ while Jovian Trojan objects (JTO) have $q > 4.2 \text{ au}$ and $4.8 \text{ au} < a < 5.4 \text{ au}$.

In what follows we will frequently refer to ‘unbiased’ and ‘debiased’ distributions. We use the term ‘unbiased’ to refer to the true distributions whereas ‘debiased’ means that the observed distributions have been corrected for observational selection effects. A perfect debiasing procedure would lead to identical unbiased and debiased distributions. We can only provide unbiased distributions in circumstances for which there is evidence that the entire population is already known e.g. main belt asteroids larger than 10 km diameter. A good introduction to various types of selection effects is given by Jedicke et al. (2002) and recent advances for quantifying these effects are described by Jedicke et al. (2014).

We will present the asteroid’s absolute-magnitude ($H$) distributions in terms of their cumulative number, $N(< H) \propto 10^{\alpha H}$, where $\alpha$ is referred to as the ‘slope’. When available or appropriate we may provide the diameter ($D$) number distribution where $N(> D) \propto D^{-b}$ and $b$ is also called the ‘slope’. Both the $H$ and $D$ versions are often colloquially referred to as the ‘size’ distribution. The slopes are generally not constant with $H$ or $D$ but are often approximately constant over some intervals. The two slope parameters are related by $b = 5\alpha$ under the assumption of a constant albedo within a population.

### 6.1 Near-Earth Objects

The Bottke et al. (2002) NEO population model has been extremely successful for the past 12 years, especially considering that it was calibrated with only 137 known NEOs. Their modeling approach utilized dynamical constraints provided by the orbital-element ‘residence-time’ distributions for NEOs originating in different source regions (essentially likelihood maps in orbital-element space). The only notable improvement to the model was the recalculation of the residence-time distributions by Greenstreet et al. (2012a) using smaller time-steps and more particles to reduce the statistical noise and provide an improved orbital model. They did not re-fit the observed NEO population but provided an improved NEO model using the Bottke et al. (2002) source weights and slope ($\alpha = 0.35$) of the $H$ distribution. The Greenstreet et al. (2012b) NEO model suggested that there exist dynamical pathways from prograde MBO orbits to retrograde NEO orbits and estimated that there are about four $H < 18$ NEOs on retrograde orbits at any time. They also concluded that one of the currently known retrograde NEOs is likely an asteroid rather than a comet.

Preliminary results from the WISE mission suggested that there are $981 \pm 18$ NEOs with $D > 1 \text{ km}$ and that the cumulative diameter distribution could be represented by a broken power-law with $b = 5$ for $D > 5 \text{ km}$, $b = 2.1$ for $1.5 < D < 5 \text{ km}$, and $b = 1.32 \pm 0.14$ for $D < 1.5 \text{ km}$ (Mainzer et al., 2011b). Their subsequent preliminary analysis (Mainzer et al., 2012) of the four NEO sub-populations (Atiras, Atens, Apollos, and Amors) suggested that there are fewer high-inclination Aten asteroids than predicted by Bottke et al. (2002), a result that was soon verified by Greenstreet et al. (2013).

Zavodny et al., 2008 derived the absolute-magnitude and orbit distribution for Atiras — objects orbiting the Sun entirely interior the orbit of the Earth (IEO) — using data obtained by the CSS. They found that the Bottke et al. (2002) NEO orbit distribution is consistent with the CSS observations and derived a nearly independent measurement of the slope of the absolute magnitude distribution ($\alpha = 0.44_{-0.23}^{+0.23}$), again, consistent with both Bottke et al. (2002) and Stuart (2001).

Temporarily-captured natural Earth satellites are a recently-recognized NEO sub-population Gruenvik et al., 2012. The average length of capture in the Earth-Moon system is about 9 months for these ‘minimoons’ and the largest object at any given time has a diameter of about 1 to 2 m assuming that their size distribution follows that observed for small Earth-impacting asteroids (Brown et al., 2002; Brown et al., 2013). Only one minimoon has been positively identified (2006 RH$_{120}$; Kowalski et al., 2009) due to their small sizes and rapid sky-plane motions but the discovery rate will most likely increase in the future as the next-generation of asteroids surveys come online (Bolin et al., 2014, and [7]).

Figs. 3 and 4 illustrate the orbit and absolute-magnitude distributions for NEOs from the preliminary work of Gruenvik et al. (2015) because 1) they used the largest currently available single-survey NEO data set (from CSS) and 2) their work is an independent data product in the sense that its development did not rely on any other NEO models. i.e., the WISE measurements were debiased assuming the orbital distribution by Bottke et al. (2002), and Greenstreet et al. (2012) used the source ratios and size distributions also from Bottke et al. (2002). The Gruenvik et al. (2015) estimate for the number of $H < 18$ NEOs agrees with Stuart (2001), and the number of $H < 17.75$ NEOs is consistent with the number of $D > 1 \text{ km}$ NEOs predicted by Stuart and Binzel (2004) and Mainzer et al. (2011). The advantage of using the results of Gruenvik et al. (2015) is that they provide 1) the debiased ($a, e, i$) orbital-element distributions and 2) an extended range in the debiased absolute magnitude number distribution to $H = 25$. The functional form of their $H$ distribution allows for a ‘wave’ (a non-constant slope) as suggested by, e.g. Harris (2013), but does not require it. They also allow a different $H$ distribution for each of their 7 source regions so that the observable NEO $H$ distribution is the sum of 7 analytic functions and the NEO orbit distribution changes slightly as a function of $H$.

### 6.2 Main Belt Objects

It is challenging to develop debiased size and orbit distributions for MBOs that extend to sizes smaller than the
completeness level (currently about $H \sim 17$; Denneau et al., 2015) because asteroid families induce discontinuities into the distributions and, contrary to NEOs, MBOs are not replenished from outside sources. That is, the MBO population is not in a steady state — it continues to erode through collisional grinding, and dynamical- and radiation-induced orbit evolution. There are two population models for the MBO orbit and absolute-magnitude distributions: the Statistical Asteroid Model (SAM; Tedesco et al., 2005) and the Pan-STARRS Synthetic Solar System Model (S3M-MBO; Grav et al., 2011). Both models were developed by starting from the unbiased orbital-element distribution of large MBOs. The MBOs were extrapolated to smaller sizes assuming a negligible correlation between size and orbit, and that the slope of the $H$-distribution is constant beyond the $H$ completeness limit at the time of the model’s development. The S3M-MBO uses a single slope for all subcomponents of the main asteroid belt whereas SAM employs different slopes for each of 15 families and 3 background populations. The maximum absolute magnitude in the S3M is correlated with perihelion distance so that it only contains synthetic objects that can reach $V < 24.5$ at perihelion at opposition, i.e. those that might be detectable by the 4-telescope Pan-STARRS, equivalent to modeling all objects in the main belt with $D > 300$ m but including objects as small as 100 m diameter on the inner edge. SAM attempted to reproduce the distribution of all MBOs with $D > 1$ km.

While these models are the most comprehensive MBO models to date they represent just the first steps in modeling this complex population. The actual population at the smallest sizes and most extreme orbits can not be simply extrapolated from larger objects and more common orbits as demonstrated by:

- **SMBAS:** the Sub-km Main-Belt Asteroid Survey (Yoshida et al., 2003) with the Subaru telescope demonstrated that the cumulative size distribution slope is shallower for sub-km MBOs ($0.5 \text{ km} < D < 1 \text{ km}$) than for $D > 5 \text{ km}$ MBOs, $b \sim 1.2$ versus $b \sim 1.8$, respectively. The depletion of sub-km MBOs is more pronounced in the outer belt ($a > 2.5 \text{ au}$) than the inner belt ($a < 2.5 \text{ au}$).

- **SKADS:** the pencil-beam-type Sub-Kilometer Asteroid Diameter Survey (Gladman et al., 2009) derived a de-biased $H$-magnitude distribution of $\alpha = 0.30 \pm 0.02$ throughout the main belt in the range $15 < H_R < 18$. Limiting the analysis to the inner main belt allowed them to extend the absolute magnitude interval to $15 < H_R < 19.5$ for which the slope is marginally shallower with $\alpha = 0.23 \pm 0.04$. A fit to the SKADS dataset does not require a decrease in the slope for $H \gtrsim 18$ but cannot rule it out.

- **Terai et al. (2013):** who suggest that high- and low-inclination MBOs have different size-frequency distributions based on observational data collected with the Subaru telescope. They interpret this as a consequence of the larger impact speed for high-inclination asteroids.

### 6.3 Trojan asteroids

Trojan asteroids orbit the Sun in a 1:1 mean-motion resonance with a planet and populate two distinct ‘clouds’ leading or trailing the planet by $\sim 60^\circ$, the Lagrange 4 ($L_4$) and Lagrange 5 ($L_5$) clouds, respectively. In what follows we will primarily discuss Jupiter’s Trojan objects (JTO) but also touch upon Trojans of other planets in the inner solar system.

The Nice model (e.g. Morbidelli et al., 2005) suggests that the JTOs originated in the outer reaches of the protoplanetary disk with semi-major axes in the range $15 \text{ au} < a < 30 \text{ au}$ and were dynamically captured by Jupiter during the repositioning of the planets after the formation of the solar system. Interestingly, the number of JTOs in the clouds appears to be unequal: Szabo et al. (2005) estimated that the $L_4 : L_5$ number ratio is $1.6 \pm 0.1$ based on SDSS data whereas Grav et al. (2011) derived an independent ratio of $1.4 \pm 0.2$ using WISE measurements. Assuming that the two values are truly independent, the error-weighted ratio of $1.58 \pm 0.08$ is more than $7 - \sigma$ from unity. The combined clouds have an $H$-distribution with a slope of $\alpha = 0.64 \pm 0.05$ in the range $9 < H < 13.5$ (Szabo et al., 2005). The equivalent slope of the cumulative size distribution is $b = 2.2 \pm 0.25$ in agreement with the preliminary result from WISE of $b \sim 2$ (Grav et al., 2011). Similar slopes have recently also been obtained by Yoshida & Nakamura (2005) using a substantially smaller sample size.

Trojan objects have also been discovered for Mars (MTO; see de la Fuente Marcos & de la Fuente Marcos (2013) and Christou (2013), for the most recent tally), Venus (VTO; de la Fuente Marcos & de la Fuente Marcos, 2014) and the Earth (ETO; Connors et al., 2011). Based on the uneven distribution of objects in the Mars $L_4$ and $L_5$ clouds (1 versus 7), and the compactness of the orbital distribution in $L_5$, both de la Fuente Marcos and de la Fuente Marcos (2013) and Christou (2013) suggest that the objects in $L_5$ have a common origin in either a collisional or a rotational break-up event. Whereas the 8 known MTOs are on orbits that are stable on Gyr timescales the known ETOs and VTOs appear to be transient captures of NEOs with kyr lifetimes.

### 7. ANTICIPATING THE FUTURE

The next decade of NEO discovery will likely be dominated by the large aperture, wide FOV, ground-based telescopes or the space-based near-IR discovery systems described below with details provided in table 5. But this NEO-centric viewpoint belies the important contributions to the detection and monitoring, follow-up and characterization, of all the asteroids in the inner solar system. Some or all of these efforts might still be dominated by smaller aperture and visible light ground-based systems. Furthermore,
we specifically address an emerging new camera technology that could impact the way we detect all types of asteroids — early tests are promising but its actual implementation awaits funding and verification.

This section is divided into three sub-sections that present our current understanding of upcoming improvements, and expected new ground- and space-based assets. The facilities in each sub-section are presented alphabetically.

7.1 Upgrades to existing facilities

Catalina Sky Survey (CSS)

The CSS team has distinguished itself in its ability to constantly improve their systems and is currently in the process of installing monolithic 10k×10k CCD cameras on both the CSS Schmidt (703) and MLS (G96) telescopes. This will effectively double the surveying capability of the CSS Schmidt allowing 3,000 to 5,000 deg$^2$ to be surveyed nightly to $V \sim 20$. The MLS telescope will enjoy a factor of 5× increase in area coverage through the addition of reducing optics and be capable of surveying ∼1,000 deg$^2$/night to $V \sim 21.5$. It is possible that the CSS Schmidt will be used to survey most of the observable sky over the course of a night or two. The repeated survey coverage will yield a more complete main belt minor planet catalog because it will be easier to link asteroid detections from night-to-night and then to other apparitions.

Further improvements will be realized by pushing the capability of linking detections to faster rates and non-linear motion. i.e. most surveys currently require that detections on a single night follow a linear trajectory even though the closest object’s path will be curved on the sky plane: since most surveys ignore the curvature it implies that many nearby, perhaps even geocentric, objects are not being identified by the current surveys. Yet another seemingly mundane ∼30% reduction in the time required for the telescope to step+settle+readout will yield a 10 to 12% increase in overall area coverage and, presumably, discovery rate.

The combined CSS and MLS telescopes should extend the completeness of the main belt minor planet catalog to an absolute magnitude well beyond the current 17.5 (Denneau et al., 2015), perhaps as deep as $H \sim 19$ (about 800 m diameter). The increased discovery rate is not expected to have any impact on the MPC processing of the reported observations.

Panoramic Survey Telescope and Rapid Response System (Pan-STARRS)

Beginning in March 2014 and continuing through at least March 2015 PS1 has been dedicated 100% to the NEO survey after which it will continue to devote 90% of its time to the search. It will be joined in late 2014 by a second, nearly identical, telescope, Pan-STARRS2, and both telescopes will be used for the NEO survey at the 90% level through at least September 2017. Doubling the number of telescopes will not double the NEO discovery rate because not all areas of the sky are equally rich in unknown NEOs.

Upgrading the CCDs in both telescopes has the potential to dramatically increase the NEO discovery rate but depends on whether funding can be identified. The existing CCDs each have a cell structure consisting of an $8 \times 8$ grid of 600×600 pixels that make the system less efficient for finding faster moving objects because they can move over the cell gaps (which are not sensitive to light), dividing the asteroid’s trail in two. Larger monolithic commercial grade low-noise CCDs will eliminate this problem, correct cosmetic problems in the existing CCDs that decrease the effective fill factor, and allow deeper NEO searches due to lower noise.

The image processing pipeline (IPP; Magnier, 2006) and moving object processing system (MOPS; Denneau et al., 2013) are both being continually tuned and improved to enhance the NEO detection efficiency.

7.2 Exciting new facilities & technologies

Asteroid Terrestrial-impact Last Alert System (ATLAS)

The University of Hawaii’s ATLAS project (Tonry, 2011) is expected to be operational in 2015 when it will begin robotically surveying the entire sky multiple times each night. The system will have two identical 50 cm Wright-Schmidt telescopes each located in separate domes, one on Mauna Loa, Hawaii, USA, and the other on Haleakala, Maui, USA. The telescopes will have 7.4° FOVs instrumented with STA-1600 110-megapixel CCDs. They expect to identify asteroids roughly in the range $13 < r < 20$ with each primary system and to identify asteroids in the $6 < r < 14$ range with auxiliary cameras co-mounted on each of the primary telescopes (The $r$ wavelength band is similar to the Johnson-Cousins $R$ band). Thus, this system could monitor the entire main belt visible in the night sky to about $r = 20$ multiple times each night.

Fly-Eye

The ESA is planning a network of small telescopes with a novel ‘Fly-Eye’ optical concept to completely scan the sky each night to identify space debris and NEOs (Cibin et al., 2012). The system’s name captures the idea that the optics create 16 sub-images of a field that are seamlessly stitched together to create a composite image with a 100% ‘fill-factor’ (the fraction of the image plane or sky that is actively instrumented — e.g. the PS1 mosaic camera system has a fill-factor of ∼75% (Denneau et al., 2013). A prototype system is currently being built that has a 6.7° × 6.7° FOV (about 45 deg$^2$) with performance equivalent to a 1 m diameter telescope.

Gaia
The ESA’s Gaia mission (e.g. Lindegren et al., 2008) will measure the positions of about a billion stars spanning the entire sky to about 24µas precision. As of 2014 June 13 there were already over 260 published, refereed, articles about the Gaia mission despite the fact that the primary survey had not even begun — 35 of those papers had both Gaia in the title and ‘asteroid’ as a keyword. There is no doubt that Gaia’s astrometric and photometric catalog will transform our ability to measure an asteroid’s position and brightness and the spacecraft should provide spectrophotometry of asteroids with V < 20. Gaia is expected to detect about 350,000 asteroids and yield spectral classifications for about a quarter of that sample (e.g. Delbo et al., 2012; Mignard et al., 2007).

Large Synoptic Survey Telescope (LSST)

The LSST has the potential to be an extremely powerful asteroid detection and discovery telescope. With an expected limiting magnitude of R ~ 24 it could discover millions of new MBOs and hundreds of thousands of NEOs during its operational lifetime. The system is expected to repeat the same fields every four nights, thus providing its own follow-up. A system this robust could obviate most other ground-based observing systems for discovery (but asteroids brighter than R ~ 18 would saturate the system and probably not be reported). Its actual performance for discovering asteroids will remain to be demonstrated because LSST intends to acquire only 2 frames/night separated by a small time interval. This strategy should pose little difficulty for linking detections to known objects but its application to discovering new objects could be limited by the false detection rate.

Space Surveillance Telescope (SST)

The US Defense Advanced Research Projects Agency’s (DARPA) SST has a 3.5 m diameter mirror and an f/1.0 Mersenne-Schmidt optical system that is currently located on Atsia Peak, NM, USA, at 2,400 m elevation within the White Sands Missile Range but is scheduled to be moved to Australia. The extremely fast telescope has a curved focal plane instrumented with curved CCDs developed specifically for the purpose. It is capable of covering several thousand deg²/night to V > 20. The SST’s primary goal is to survey the geosynchronous belt but DARPA is considering providing some of the survey time to an asteroid survey (Monet et al., 2013), much like the LINEAR system (Stokes et al., 2000) was tasked for NEO surveying when not searching for satellites. LINEAR set the performance bar when it joined the NEO search and there is little doubt that the SST could do the same if it brings its new-technology, large-aperture, large-field, fast-optics, and rapid-readout system to bear on the NEOs.

Synthetic tracking

Shao et al. (2014) describe the application of two new technologies to asteroid detection that might, if successful, advance the field over the next decade. They combine new low-noise fast-readout CCDs with the computational power of graphics processing units (GPU). Their CHIMERA camera with a 2.5’ × 2.5’ FOV has already been tested on the Palomar 5 m telescope where they obtained images at 2 Hz (much faster rates will be used in standard operations) and then implemented the standard shift-and-add technique on their GPU to ‘synthetically track’ an asteroid. They hope to upgrade their camera to a 8’ × 8’ FOV in the next couple years which will enable rapid searching, albeit over limited areas, for fast-moving asteroids to as faint as V ~ 25.

7.3 Possible future space-based missions

Near-Earth Object Camera (NEOCam)

NEOCam is a proposed NASA Discovery-class mission whose goal is to survey for NEOs from a space-based platform operating from near the Earth-Sun L1 point. Given the success of the NEOWISE mission (Mainzer et al., 2011a) we expect that the substantially larger telescope surveying 100% of the time for NEOs will be extremely successful. NEOCam should excel at detecting NEOs due to their strong emission in their two proposed 6 to 10 µm band.

Sentinel

The philanthropic non-profit B612 organization (https://b612foundation.org) is attempting to raise private donations to fund the construction, launch and operations of a spacecraft specifically designed to identify ‘threatening asteroids whose orbits approach Earth’, i.e. PHOs, and identify many other NEOs and MBOs in the process. They hope to launch the spacecraft in 2017-2018 into a Venus-like elliptical orbit for its 6.5 yr mission. The orbit is particularly effective for identifying PHOs since they must pass through a torus of 0.05 au diameter centered on Earth’s orbit that is always exterior to the spacecraft’s orbit. They expect to survey ~ 165 deg²/hour with a 24 million pixel IR camera (5 – 10.2 µm) that will have an 11 deg² FOV.

8. SUMMARY & CONCLUSIONS

The NEO surveys have improved dramatically since publication of Asteroids III, yielding 8 times more NEOs and...
10× more MBOs in the last five years than in the five years before Asteroids III. This accomplishment is all the more impressive considering that none of the current survey telescopes was designed with NEO observations in mind — they are all repurposed instruments originally designed for entirely different operations.

The situation could change in the next decade with the introduction of new ground-based and/or space-based surveys specifically designed for NEO observations (e.g., ATLAS, NEOCam, Sentinel). These new facilities suggest that we can expect an increased discovery rate of asteroids in the near future but they will require a concomitant operational evolution. For instance, existing NEO surveys still rely on human vetting of asteroid tracklet candidates but this process might not be tenable if the discovery rate increases another order of magnitude. It seems clear that the surveys will need to implement regular self-follow-up, improved software processing, and coordinate their surveying and follow-up efforts through a centralized organization (cf. NASA’s Office of Inspector General’s report on the NEO effort; IG-14-030, 2014 Sept 15).

Improvements to the existing surveys and the development of the next-generation surveys will push the completeness limits of all the inner solar system’s asteroid subpopulations to ever smaller sizes to allow us to study the unbiased orbit and size distributions. Debiasing the populations to even smaller sizes requires attention to the surveying plan and measuring the system’s detection efficiency from the outset. Indeed, the limiting factor in generating good debiased models of the inner solar system’s asteroid populations is the lack of well-calibrated survey data e.g., detection efficiencies, per detection astrometric and photometric uncertainties, etc..

Most of the largest, globally-devastating potentially hazardous objects larger than 1 km diameter are now known but there remains a residual impact risk from the remaining unknown ∼ 10% and sporadic long-period comets. Perhaps surprisingly, that risk is now comparable to that of sub-100 m diameter objects because of 1) the reduced slope of the NEO SFD in the 100 m to 1 km diameter range and 2) the partial discovery of some of the objects in the intermediate range. In any event, there are active plans and funding to address the residual risk in the next decade, mostly funded by NASA and mostly based in the United States. The scientifically interesting and space-based resource utilization options for the much more numerous objects of < 100 m diameter remains to be explored. About a third of the discovered NEO population is < 100 m in diameter (almost 4,000 objects!) but about 3/4 of them have a MOID < 0.05 au, placing them in the sub-PHO category only by virtue of their mass. These objects may be discovered days to weeks before impact by ground-based surveys like the upcoming ATLAS and LSST projects but the maximum ground-based detection efficiency for objects on the scale of the Chelyabinsk impactor is only about 50% because about half of them will approach Earth from the direction of the Sun — like the Chelyabinsk impactor. The only way to detect and characterize these objects before impact is with a space-based detection system like NEOCam or Sentinel.

It is likely that physical characterization of asteroids will lag ever farther behind their discovery simply because of the much larger phase-space of possible ‘physical characterization’ and the dedicated resources that must be applied for each measurement to individual asteroids. It seems that the only solution is to continue the process of limiting physical characterization to the most interesting targets and developing new systems that allow characterization in a multi-object mode. For instance, NEOWISE, NEOCam and Sentinel have or plan to measure accurate asteroid diameters in the IR while they survey for unknown NEOs. Similarly, the already-operational Gaia mission will measure main belt asteroid masses, densities, shapes, pole orientations and the impact of the Yarkovsky effect on their orbital evolution.

In closing, the only certainty about the future of asteroid discovery, characterization, and exploration, is that we can expect great progress in the next decade leading to the publication of Asteroids V.

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### Table 1

**Top 10 NEO surveys (2003-2014).**

| Rank | NEOs  | Survey   | Location               | P.I.        | Aperture (m) | f-ratio (f) | FOV (deg²) | pixel scale (″/pix) | Obs. Code |
|------|-------|----------|------------------------|-------------|--------------|-------------|-------------|---------------------|-----------|
| 1    | 2,910 | CSS      | Mt. Lemmon, AZ, USA    | E. Christensen | 1.50         | 2.0         | 1.2         | 1.0                 | G96       |
| 2    | 1,952 | CSS      | Mt. Lemmon, AZ, USA    | E. Christensen | 0.68         | 1.8         | 8.2         | 2.5                 | 703       |
| 3    | 1,364 | LINEAR   | White Sands, NM, USA   | G. Stokes    | 1.0          | 2.2         | 2.0         | 2.25                | 704       |
| 4    | 1,303 | Pan-STARRS1 | Haleakala, HI, USA | R. Wainscoat | 1.8          | 4.0         | 7           | 0.26                | F51       |
| 5    | 574   | Spacewatch | Kitt Peak, AZ, USA     | R. McMillan  | 0.9          | 3.0         | 2.9         | 1.0                 | 691       |
| 6    | 462   | CSS      | Siding Spring, Australia | S. Larson  | 0.5          | 3.5         | 4.2         | 1.8                 | E12       |
| 7    | 166   | LONEOS   | Anderson Mesa, AZ, USA | E. Bowell   | 0.6          | 1.8         | 8           | 2.6                 | 699       |
| 8    | 162   | NEOWISE  | Earth polar orbit      | A. Mainzer  | 0.4          | 3.375       | 0.6         | 2.75/5.5†          | C51       |
| 9    | 119   | NEAT/AMOS | Palomar, CA, USA       | E. Helin    | 1.2/1.2      | 3/2.0       | 5/2.0       | 1/1.25              | 644/608   |
| 10   | 95    | La Sagra Sky Survey | Granada, Spain | J. Nomen  | 3×0.45       | 2.8         | 1.5         | 2×1.5 & 2          | J75       |

**Note.**—The top 10 NEO surveys discovered > 96% of all NEOs identified during the time period from 2003 Jan 1 through 2014 Nov 18. Columns are: Rank and number of NEOs discovered , Survey name or acronym, location of the survey site, name of the original or current principal investigator (PI), telescope aperture in meters, the f-ratio (focal length of primary mirror divided by its aperture), the FOV in square degrees, the image scale in arc seconds per pixel, and the site’s IAU observatory code.

†2.75″/pix in the 3.4, 4.6, and 12 um channels and 5.5″/pix in the 22 um channel.

### Table 2

**Minor Planet Center holdings as of 2014 Nov 6**

| Type               | objects |
|--------------------|---------|
| Numbered           | 415,688 |
| Multi-opposition   | 133,306 |
| 1-opposition       | 115,042 |
| 2-night            | ~165,000|
| 1-night            | O(3,000,000) |

**Note.**—The MPC data files contained a total of 118,328,160 observations as of 2014 Nov 6.
### Table 3
**Top 10 Asteroid Discovery Surveys (of all time)**

| Rank | Survey or Discover | Obs. code | Discoveries | Operations   |
|------|--------------------|-----------|-------------|--------------|
| 1    | LINEAR             | 704       | 141,577     | 1997-2010    |
| 2    | Spacewatch         | 691       | 85,338      | 1985-present |
| 3    | NEAT/AMOS          | 644/608   | 31,116      | 1995-2007    |
| 4    | Mt. Lemmon Survey  | G96       | 30,422      | 2004-present |
| 5    | CSS                | 703       | 20,664      | 1998-present |
| 6    | LONEOS             | 699       | 19,856      | 1998-2012    |
| 7    | Haleakala-AMOS     | 608       | 7,475       | 1995-2003    |
| 8    | PLS/T-1,T-2,T-3    | 675       | 6,796       | 1960-1977    |
| 9    | E. Elst†           | 809       | 5,650       | 1983-2012    |
| 10   | Pan-STARRS 1       | F51       | 4,684       | 2010-present |

**Note.**—Rankings are from 2014 September 14. Columns are: rank of the survey in terms of the number of asteroid discoveries credited to the survey; Survey name, acronym, or observer; the site’s IAU observatory code; current number of asteroid discoveries credited to the survey; time period of survey operations.

†Belgian professional astronomer

### Table 4
**Top 10 Asteroid Astrometric follow-up Sites (2011 to 2014)**

| Observatory       | Obs. Code | Location | Lead(s)             | Telescope(s) aperture | Limiting V Mag. | NEOs Total 2011-2014 | NEOs V > 20 2011-2014 |
|-------------------|-----------|----------|---------------------|-----------------------|-----------------|-----------------------|------------------------|
| ARO               | H21       | IL, USA  | R. Holmes           | 0.5m; 1.4m            | 22              | 3,418                 | 2,112 (62%)            |
| Cerro Tololo      | 807       | Chile    | T. Linder, R. Holmes| 0.41m                 | 20-21           | 2,563                 | 1,659 (65%)            |
| Spacewatch II     | 291       | AZ, USA  | R. McMillan         | 0.9m; 1.8m            | 20-23           | 2,511                 | 2,149 (86%)            |
| Schiaparelli      | 204       | Italy    | L. Buzzi            | 0.38m; 0.6m           | 22              | 1,821                 | 567 (31%)              |
| Sandlot           | H36       | KS, USA  | G. Hug              | 0.56m                 | 22              | 1,040                 | 437 (42%)              |
| Great Shefford    | J95       | England  | P. Birtwhistle      | 0.4m                  | 20-21           | 968                   | 388 (40%)              |
| Mauna Kea         | 568       | HI, USA  | D. Tholen, R. Wainscoat| 2.2m; 3.6m       | >23             | 937                   | 827 (88%)              |
| Desert Moon       | 448       | NM, USA  | B. Stevens, J. Stevens | 0.3m                 | 20-21           | 896                   | 314 (35%)              |
| Magdalena Ridge   | H01       | NM, USA  | W. Ryan, E. Ryan    | 2.4m                  | 24              | 854                   | 573 (67%)              |
| Tenagra II        | 926       | AZ, USA  | M. Schwartz         | 0.8m                  | 18-21           | 782                   | 402 (51%)              |

**Note.**—The sites are ranked and listed by total number of NEOs observed at each observatory from 2011 June thru 2014 June. Columns are: observatory name or acronym; the site’s IAU observatory code; the site’s location; the name of the current lead, observer, or principal investigator; telescope aperture in meters; limiting magnitude in the V band; total number of NEOs observed during the four years from 2011-2014 inclusive; and the number of NEOs observed at each facility with V > 20 (and the fraction of NEOs with V > 20). The last column is provided to illustrate that some facilities excel at faint object follow-up.
| Survey | Site | Lead(s) | Aperture (m) | $f$-ratio | FOV (deg$^2$) | pixel scale ("/pix) | IAU Obs. Code |
|--------|------|---------|--------------|------------|--------------|-------------------|---------------|
| ATLAS  | Haleakala, HI, USA | J. Tonry | 0.5 | 2.0 | 30 | 1.86 | TBD |
| ATLAS  | Mauna Loa, HI, USA | J. Tonry | 0.5 | 2.0 | 30 | 1.86 | T08 |
| CSS    | Schmidt, AZ, USA | E. Christensen | 0.68 | 1.8 | 8.2 | 2.5 | 703 |
| CSS    | Mt. Lemmon, AZ, USA | | 1.50 | 2.0 | 1.2 | 1.0 | G96 |
| Gaia   | Earth-Sun L2 | ESA, T. Prusti | 1.45 × 0.5 | n/a | 0.42 | 0.059×0.18 | TBD |
| Fly-Eye | TBD | ESA SSA-NEO D. Koschny & G. Drolshagen | 1.1 | 2.0 | 45 | 1.5 | TBD |
| LSST   | Cerro Pachon, Chile | LSSTC* | 8.4 (6.4) | 1.2 | 9.6 | 0.22 | TBD |
| Pan-STARRS2 | Haleakala, HI, USA | R. Wainscoat | 1.8 | 4.0 | 7 | 0.26 | F51 |
| Spacewatch | Kitt Peak, AZ, USA | R. McMillan | 0.9 | 3.0 | 2.9 | 1.0 | 691 |
| Spacewatch | | | 1.8 | 2.7 | 0.6 | 1.0 | 291 |
| SST    | Atom Peak, NM, USA | G. Stokes | 3.5 | 1.0 | 6 | 0.89 | G45 |

**Note.**— Listed in alphabetical order by survey name. Fly-Eye, Gaia, LSST, and SST are not focussed on NEO or asteroid discovery but could make major contributions to the inventory. We provide site-specific information even for surveys that use multiple sites and/or telescopes. The list includes only funded surveys as of publication of Asteroids IV. The columns are: Survey, Site, Principal Investigator, telescope aperture in meters, the $f$-ratio (focal length of primary mirror divided by its aperture), the FOV in square degrees, the image scale in arc seconds per pixel and the IAU observatory code. *LSST is operated by the LSST Corporation. †LSST will have an unusually large secondary mirror and 'dual-purpose' primary mirror so we also provide the system's effective aperture.
Fig. 1.— Main belt and near-Earth object discovery statistics since 1800 in five year intervals. The time periods corresponding to serendipitous visual and photographic asteroid discovery is indicated as are the time periods for photographic and CCD surveys. The Palomar-Leiden Survey (PLS; VanHouten et al., 1970) in 1960 was particularly ahead of its time as it discovered $>10 \times$ more asteroids in a few months than were being discovered over 5 years at the time. It took another decade before the discovery rates regularly matched the PLS rate.
Fig. 2.—(top) Eccentricity and (bottom) inclination vs. semi-major axis for all known asteroids in the inner solar system available in the MPC database as of 2014 June 8. Note that the completeness, the fraction of the actual population that is known, varies as a function of semi-major axis so that these panels do not provide a good representation of the actual distribution of asteroids (see fig. 3). The clump of objects with $2 \text{ au} \lesssim a \lesssim 3.5 \text{ au}$ are the main belt objects and the clump just under $4 \text{ au}$ are the dynamically separated Hilda population. The group just beyond $5 \text{ au}$ are the Jupiter Trojan objects (JTO). The near-Earth objects are those above the (solid white) $1.3 \text{ au}$ perihelion line in the top panel. Objects on the left of the aphelion line at $1 \text{ au}$ in the top panel have orbits entirely inside the Earth’s orbit. The enhancement of NEOs along the $q \sim 1 \text{ au}$ in the top panel is an observational selection effect that makes it easier to detect those objects from Earth. The ‘diagonal feature’ in the top panel near $a = 3.7 \text{ au}$ and $e = 0.2$ are all WISE spacecraft discoveries that lack proper follow-up observations and only have a very rough eccentricity-assumed orbit.
Fig. 3.— Debiased (top) eccentricity and (bottom) inclination vs. semi-major axis for asteroids with $H < 18$ in the inner solar system. For NEOs we use the Granvik et al. (2015) model. For MBOs and JTOs we assume a negligible correlation between orbital elements and size, and extrapolate the orbit distribution from the assumed completeness levels of $H = 15$ and $H < 12.5$, respectively, using the slopes shown in Fig. 4. The total number of NEOs, MBOs and JTOs with $H < 18$ are predicted to be about 1500, 1,300,000, and 600,000, respectively. The near-Earth objects are those above the 1.3 au solid white perihelion line in the top panel. Objects on the left of the aphelion line at 1 au in the top panel have orbits entirely inside the Earth’s orbit.
Fig. 4.— Known, fit, and extrapolated $H$-distributions of near-Earth (NEO), main belt (MBO) and Jupiter Trojan objects (JTO). The ‘known’ population is the number of objects in the MPC database as of 2014 June 8. The ‘fitted’ populations represent the debiased distributions over specific $H$ ranges for NEOs and MBOs as derived by Granvik et al. (2015) and Gladman et al. (2009), respectively. The ‘Harris’ NEO HFD is provided for reference and described in Harris et al., this volume. For JTOs we use a slope of $\alpha = 0.48$ and assume that there are $10^6$ JTOs with $H < 18.5$ — the slope is slightly shallower but still in statistical agreement with that derived by Szabo et al. (2005). The NEO $H$-distribution has to become shallower for $H > 25$ to match the bolide data (Brown et al., 2013). The ‘extrapolated’ populations for MBOs and JTOs are simple linear extensions of the HFD to larger $H$ (smaller diameters) for the purpose of comparison with the other populations in an extended $H$ range.