Future Surveys of the Kuiper Belt

Chadwick A. Trujillo
Gemini North Observatory

The next decade of Kuiper belt object (KBO) science will be completely dominated by the output of two surveys. These two surveys, the Panoramic Survey Telescope and Rapid Response System (Pan-STARRS) and the Large Synoptic Survey Telescope (LSST), will increase the total number of known KBOs by factors of 25 to 150 over the next decade. This discovery rate will not be uniform — it will come as a large flood of information during the first year of operation. If software development allows, additional depth may be gained in successive years if data can be combined across years to find bodies that are too faint to be detected in an individual visit. Not only will the surveys increase the number of objects dramatically, but they will also be sensitive to heliocentric distances far beyond 100 AU due to their multiyear survey methodology. In this work, we outline a basic timeline of operation of these two powerful surveys and the science that will be enabled by their data output, as well as other significant advances in KBO surveys expected in the next decade.

1. INTRODUCTION

The coming decade should see a dramatic increase in our knowledge of the Kuiper belt object (KBO) population due entirely to new telescopic survey experiments. This advance in our knowledge of the Kuiper belt population statistics is hard to underestimate, as even the most conservative estimates suggest increases of factors of 25 in the total number of known KBOs as well as the possibility of finding bodies in solar orbit well beyond 100 AU.

Methods employed in Kuiper belt surveys can be very crudely divided into two categories: (1) all-sky shallow surveys and (2) targeted deep surveys. In each of these categories, past surveys have made a large scientific impact. It is difficult to quantify the impact of a survey, but by examining refereed publications and citations directly related to a given survey, one can get an indication of how important these two types of surveys are to the larger scientific community. No survey has covered the entire sky in the search for solar system bodies, but the closest modern digital survey (cf. *Tombaugh,* 1946) is the Caltech wide-area survey, which has covered most of the sky available from Palomar Mountain (roughly 25,000 deg^2) to about 21st mag in a custom filter encompassing approximately the ri bandpasses, roughly equivalent to $m_R \sim 21.5$ (*Trujillo and Brown,* 2003). This single survey has discovered many candidate dwarf planets, including (50000) Quaoar, (55565) 2002 AW_{197}, (90377) Sedna, (90482) Orcus, (136108) 2003 EL_{61}, (136199) Eris, and (136472) 2005 FY_9, which have led to over 20 refereed publications by a variety of authors, most of which are about the physical surfaces of these relatively bright bodies (*Hughes,* 2003; *Marchi et al.,* 2003; *Trujillo and Brown,* 2003; *Brown and Trujillo,* 2004; *Morbidelli and Levison,* 2004; *Stevenson,* 2004; *Jewitt and Luu,* 2004; *Wickramasinghe et al.,* 2004; *Barucci et al.,* 2005; *de Bergh et al.,* 2005; *Cruikshank et al.,* 2005; *Stern,* 2005; *Trujillo et al.,* 2005; *Gaudi et al.,* 2005; *Brown et al.,* 2005; *Matese et al.,* 2005; *Doressoundiram et al.,* 2005; *Licandro et al.,* 2006; *Rabinowitz et al.,* 2006; *Barkume et al.,* 2006; *Brown et al.,* 2006; *Bertoldi et al.,* 2006; *Trujillo et al.,* 2007). These 20 papers have about 60 citations combined, which is likely an underestimate of the impact of the survey as all of the publications are less than a few years old. The targeted deep surveys are responsible for most of the dynamical information known about the Kuiper belt population. The impact of these surveys is also difficult to estimate; however, the 12 published surveys reviewed in the chapter by Petit et al. have a combined citation count of about 400 (*Irwin et al.,* 1995; *Jewitt et al.,* 1998; *Gladman et al.,* 1998; *Chiang and Brown,* 1999; *Sheppard et al.,* 2000; *Larsen et al.,* 2001; *Trujillo et al.,* 2001a,b; *Gladman et al.,* 2001; *Bernstein et al.,* 2004; *Elliot et al.,* 2005; *Petit et al.,* 2006). At roughly 30 citations per paper, this is well above the astronomy average of 4 to 10 citations per paper, depending on the journal (*Henneken et al.,* 2006). Even more of an example of the scientific utility of survey work is the pivotal work of *Jewitt and Luu* (1993), leading to the discovery of the first KBO, (15760) 1992 QB_1, a single paper that has been cited more than 160 times. Thus, the impact of both all-sky surveys as well as targeted surveys has been very high for the Kuiper belt. The next decade will see the most significant impact from all-sky surveys, although some additional impact can be made in targeted deep surveys.

The two largest survey projects of the next decade will be the Panoramic Survey Telescope and Rapid Response System (Pan-STARRS) and the Large Synoptic Survey Telescope (LSST). Both Pan-STARRS and LSST will cover the whole sky to red magnitude $m_R = 24$ or better, at least 10 times fainter than the current state of the art in all-sky

TABLE 1. Current and future survey power.

Instrument	Site	D (m)	Ω (deg²)	θ (arcsec)	SP*	All Sky?†	Science Start
LSST	Cerro Pachón	6.7‡	10.0	0.7	720	yes	2014
Pan-STARRS PS4	Mauna Kea	3.2§	7.0	0.5	225	yes	2010
VISTA (Visible)	Cerro Paranal	4.0	3.0	0.6	105	yes	2010?¶
Pan-STARRS PS1	Haleakalā	1.6§	7.0	0.6	39	yes	2008
DCT	Happy Jack, AZ	4.2	2.0	0.8	43	no?**	2009
VLT Survey Tel.	Cerro Paranal	2.6	1.0	0.6	15	no††	2008?
Caltech QUEST	Palomar	1.2	10.0	2.0	3	yes	2001
SkyMapper	Siding Spring	1.3	8.0	2.0	3	yes	2008?
Subaru Suprime	Mauna Kea	8.0	0.3	0.5	51	no	2000
CFHT Megacam	Mauna Kea	3.6	1.0	0.7	21	no	2004
Magellan IMACS	Las Campanas	6.5	0.2	0.6	18	no	2003
MMT Megacam	Mt. Hopkins	6.5	0.2	0.8	8	no	2004
UH 2.2 m 8 k	Mauna Kea	2.2	0.3	0.7	2	no	1995

Current and future surveys divided into dedicated survey telescopes (top) and other instruments (bottom). The table is ordered by survey power (SP) in each of the sections. Future instruments for nonsurvey telescopes were omitted, as were surveys with SP <1.

* Defined in equation (1), units are $m^2 deg^2 arcsec^{-2}$.
† Given reasonable assumptions, can the telescope survey the entire sky for KBOs? Telescopes with large fractions of other commitments are marked "no."
‡ The LSST will have an unobstructed aperture similar to a 6.7-m-diameter mirror, although the actual outer mirror diameter will be 8.4 m.
§ The unobstructed aperture of each of the Pan-STARRS telescopes is equivalent to 1.6 m, although the outer diameter is 1.8 m.
¶ Note that VISTA was recently shipped with an infrared camera, which is low efficiency for KBO discovery due to limited field size and high telluric background, but may have a visible camera added at an unspecified future date.
** It is currently unknown if the Discovery Channel Telescope (DCT) will operate in survey mode.
†† The VLT Survey Telescope will likely cover only a small amount (~300 deg²) of the ecliptic in a mode conducive to KBO detection due to the high demand for the telescope.

surveys, the Caltech survey (*Trujillo and Brown,* 2003). In terms of raw numbers, we should expect the total number of KBOs to increase dramatically, from the current small fraction (~1%) of all KBOs larger than 100 km in diameter cataloged to *all KBOs* larger than 100 km cataloged. In addition, the deepest surveys will be able to image ~10 times the area of the current deepest surveys, allowing the detection of significant number of the smallest (~25 km diameter) KBOs. This chapter will deal only with the impact of the various surveys on the Kuiper belt in the next decade. Each of these surveys has many other programs of research beyond the scope of this work, from the most distant bodies in the universe to the near-Earth asteroid population. For more detailed accounts of such survey products, consult the websites for Pan-STARRS (*pan-starrs.ifa.hawaii.edu*) and LSST (*www.lsst.org*).

Targeted deep surveys are also a possibility and require a large aperture and large field, as they study a small patch of sky to very faint limits by imaging the same field many times. There are likely to be several very deep surveys conducted by independent researchers using the largest telescopes in search of the very faintest KBOs, including the use of Pan-STARRS and LSST themselves, both of which have deep surveys on selected sky regions planned. However, most of these deep sky regions will not be much deeper than surveys that have already been conducted, although they will cover significantly more area. The targeted deep surveys are discussed in more detail in section 2.5.

2. OVERVIEW OF SURVEYS

We rank the relative strengths of existing and future surveys in Table 1, which outlines the basic parameters of various facilities. Etendue is the traditional method of measuring a survey's strength, consisting of mirror area [approximated as $\pi(D/2)^2$, where D is telescope diameter] multiplied by the field of view Ω. Although widely used, etendue tells only part of the story. Image quality is critical to any survey, so site selection is very important. Thus the median seeing θ of a survey's site must also be included in estimates of survey power. Total survey power (SP) can be estimated by the formula

$$SP = \pi\left(\frac{D/2}{m}\right)^2\left(\frac{\Omega}{deg^2}\right)\left(\frac{arcsec}{\theta}\right)^2 \quad (1)$$

following the definition in *Jewitt* (2003). Using either the etendue or SP calculation, one finds that the two main surveys of interest in coming years are Pan-STARRS and LSST. In this section, we briefly introduce some of the major survey products, with a more detailed look at both Pan-STARRS and LSST in the next section.

It must be noted that the survey power only estimates the ability of a survey to discover KBOs on an instrumental level. An even more important component is the fraction of time a survey will spend looking for KBOs. A com-

parison of operational models is very difficult to make for future surveys as much of the instrumental capabilities are still in flux. Nonetheless, all the dedicated surveys described in Table 1 have proposed placing significant resources into survey methodology conducive to KBO discovery. In most, KBO discovery is a cornerstone of the proposed survey products. Thus, factors of a few differences in SP can be overcome by adjusting fractions of time allocated to KBO surveys, but differences beyond this are unlikely to occur.

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

The final Pan-STARRS project configuration (called PS4) will consist of four 1.8-m-diameter telescopes either in a common mount or in four independent mounts. Each telescope will have a 7-deg^2 field of view with a camera system independent of the other telescopes. The major innovations of Pan-STARRS over current survey telescopes are (1) cost reduction by combining four smaller telescopes into a single system; (2) the use of Orthogonal Transfer CCDs (OTCCDs), which allow for solid state tip/tilt image compensation across the focal plane; (3) site selection to take advantage of the excellent seeing on Mauna Kea, Hawai‘i, or Haleakalā, Maui; and (4) use of a wide gri filter for solar system targets. The gri filter allows a gain of about 0.4 mag over a simple r or R filter as it covers roughly three times the bandwidth with a ~ $\sqrt{4}$ increase in background noise. The final system will thus have the equivalent of a magnitude depth of m_R = 24.0 mag (5σ detection) in about 60 s. The performance of the OTCCDs is quite critical to the system's effectiveness, as the power SP of any survey is inversely proportional to the square of the seeing. On-sky performance for the entire array of OTCCDs is not currently available, but if they performed as expected, it seems that 0.5 arcsec median seeing is a reasonable performance for purely tip/tilt correction on Mauna Kea. The plate scale of Pan-STARRS will be 0.3 arcsec per pixel, meaning that the field may be slightly undersampled in the best conditions, and adequately sampled in poor conditions.

The Pan-STARRS prototype telescope (PS1) achieved first light on Haleakalā, Maui, on June 30, 2006, and is currently funded under a grant from the U.S. Air Force. The telescope mount and enclosure are pictured in Fig. 1. The camera is still under development with the first OTCCDs being tested in the Pan-STARRS laboratory. The timescale for moving the project from the single telescope PS1 prototype to the final four-telescope system, PS4, is currently unclear; however, routine operations of PS1 are expected in 2008 and PS4 will likely be on the order of two years after this. For the sake of this article, we will assume that PS4 will be fully operational beginning in 2010.

The final PS4 system will be able to observe the entire visible sky from Hawai‘i, about 30,000 deg^2 once per week, with the solar system survey focusing on the opposition area. Thus, in a single year, the PS4 system should be able to find all KBOs brighter than red magnitude m_R ~24 visible from Hawai‘i in terms of single visit depth. The prototype PS1 system will be able to perform similarly, although with somewhat reduced depth. Final performance will greatly depend on the observing strategies employed, in particular how much time is allocated to the solar system survey compared to more distant science goals. The major source of construction funds were granted through the U.S. Air Force to find near-Earth asteroids (NEAs). However, science goals parallel to the NEA task such as KBO detection and other time-variable science products have been instrumental in granting funding to the project. Although NEAs have much larger rates of motion (~100 arcsec/h) than the KBOs (~3 arcsec/h), the two can be found simultaneously if the field of view is large enough. For example, a 1-h cadence between visits would easily allow KBO detection without sacrificing NEA detection capability for the PS1 7-deg^2 field of view. Thus, it is very likely that KBO detection will be one of the primary activities of PS1 and PS4.

Fig. 1. The Pan-STARRS PS1 prototype telescope located atop Haleakalā, Maui. The final Pan-STARRS PS4 will consist of four PS1 type telescopes, likely in a single enclosure and possibly in a single mount on either Haleakalā, Maui, or Mauna Kea, Hawai‘i.

2.2. Large Synoptic Survey Telescope (LSST)

The Large Synoptic Survey Telescope (LSST) is in the planning stages and represents the deepest all-sky survey that will be undertaken in the next decade. One potential mirror and mount design is pictured in Fig. 2. The LSST

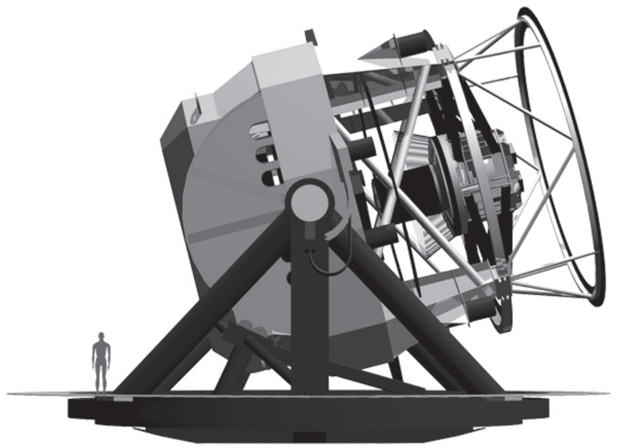

Fig. 2. The LSST design, a single 8.4-m telescope to be located at El Peñón, Cerro Pachón, Chile.

will consist of a 8.4-m-diameter telescope with a 10-deg^2 field of view. Due to the three-mirror design of the LSST, a 5-m-diameter section of the primary is obscured, yielding a clear aperture equivalent to a 6.7-m-diameter unobscured mirror. The main camera of interest to wide-field surveys will be a 3 gigapixel focal plane array. The largest technical obstacle to overcome in the design of LSST is image quality. Since the telescope is a very fast design, it has a very narrow depth of field, requiring strict tolerance on the placement of the arrays in the focal plane, to approximately 10 μm, or less than the size of a single detector pixel. The plate scale of the LSST will be 0.2 arcsec per 50 μm pixel, so therefore should be Nyquist-sampled in all conditions.

First light is scheduled for the end of 2012 with science operations beginning in 2014. The LSST will be located on Cerro Pachón (near the Gemini South and SOAR telescopes), at the El Peñón summit in Chile. The current plans for the LSST estimate that it will achieve a 5σ detection for a $m_R = 24.5$ AB magnitude star (equivalent to an $m_R = 24.25$ KBO for average KBO colors in the Vega magnitude system) when observing in the r band for 30 s per visit. Thus, while the single-visit depth of LSST is only slightly deeper than Pan-STARRS, the total number of visits available to LSST is a factor of ~3 larger, roughly the ratio between the two survey SP values. The final depth achieved by the survey will depend on the total number of visits to a single point, which is highly dependent on survey methodology, as discussed later.

2.3. The Case for Ultradeep Multiyear Detection Software

The software effort for finding moving objects is daunting for both Pan-STARRS and LSST. Each image will require 2–6 GB of disk space for the surveys. With one or two visits every minute, several terabytes of data are expected every operational night. Finding moving objects in this vast amount of data is a soluble problem only due to rapidly increasing computing power [i.e., Moore's law (from *Moore,* 1965)]. Each survey will achieve roughly similar single-visit depth, as the smaller Pan-STARRS will spend longer at each location and use a wider filter than the LSST. Thus, the total depth available to each survey will depend very critically on the ability to find moving objects beyond the single-visit depth. The software methods to detect objects beyond the single-visit depth by combining data collected over months or years are very computationally intensive, but are quite important if the full potential for each survey is to be realized.

Such an ultradeep multiyear map will certainly be produced for stationary objects as both Pan-STARRS and LSST consider this a primary science goal. However, producing a similar product for moving objects is many orders of magnitude more difficult than the original single-image identification process. Such methods have already been developed for groundbased and spaceborne KBO surveys with time bases of nights to months (*Gladman et al.,* 1998; *Bernstein et al.,* 2004). However, searching for objects over multiple years is a considerably more difficult proposition, as nonlinear orbital motion must be estimated. The computational requirements for analyzing an entire multiyear all-sky survey for all possible KBOs are not practical. However, a more limited search is computationally possible, even for the LSST, which will generate more data than any of the other surveys considered.

We first consider analyzing a single years' data confined to within 10° of the ecliptic for the LSST, the most data-intensive of the future surveys. Since the LSST proposes to cover the whole sky several times each lunation, a given ecliptic longitude will be visible to the LSST for about 6 months of the year with about 20 visits to a given field per year. Thus, on a monthly basis, roughly 600 deg^2 of sky imaged 20 times each need to be searched for bodies beyond the single-visit detection limit. Storage requirements are easily satisfied for this project, as with a 0.2 arcsec/pixel plate scale roughly ~10 TB of data per month will be analyzed, well within current (2008) technology as 1 TB disks are now available for less than $250.

Processing requirements are much more difficult to overcome. The closest work to the LSST is the HST survey of *Bernstein et al.* (2004), who found the number of required grid points for image shifting and combining follows $P^{-5}\Delta T^3$, where P is roughly equivalent to the image quality and T is the timebase. The HST search required several CPU years for a 2.4-GHz Pentium 4 processor to search $\Delta T = 1$ d at $P = 0.03$ arcsec for 5×10^9 pixels. A deep LSST ecliptic survey would require days, $\Delta T \sim 150$ arcsec and roughly 4×10^{12} pixels, increasing the processing requirement by a factor of ~200 over the *Bernstein et al.* (2004) work. This requires roughly 10^3 CPU years for a single 2.4-GHz Pentium 4 processor. Since we require a monthly cycle time for the processing, this requires a total of ~10^4 CPUs, or ~10 Tflops. Such a CPU is available for ~$100 street price as of this writing, but by 2014, the first year of LSST operation, Moore's law predicts that prices should fall by a factor

of ~10, allowing such a search to be feasible for ~\$200K, likely a small fraction of the entire LSST construction budget. As the LSST already plans to have about 60 Tflops of computing power, a deep multiyear search would require a 15% increase in the total computing power of the LSST project, while increasing KBO discovery depth by 1.6 mag per year.

A limited multiple-year deep survey is also computationally feasible. To allow multiple years, each year would have to be processed independently using the method described above to produce a list of candidate objects. Objects above the formal ~5σ significance level for a single year's worth of observations could be immediately reported as real with preliminary orbits published. Objects below the ~5σ significance level would be saved until the second year's data was collected and analyzed. If two ~3σ objects were found on successive years with similar orbits, then they could be considered a real object. Recomputation of the candidate object's orbit would be only a marginal computational requirement as once an object's orbit is roughly known, only a small amount of phase space must be searched for orbital refinement.

The extra computational effort is well worth the cost due to the steep number density of KBOs, especially for the steeper size distribution of the $22 < m_R < 23.5$ KBOs. *Bernstein et al.* (2004) describe a double power-law model where the medium faintness $m_R \sim 22$ follows a power law of $\alpha_1 = 0.88$ and the very faintest KBOs may be described by a shallower power law with $\alpha_2 = 0.32$. By combining data collected during adjacent years, a magnitude gain can be realized in the background limited case. Such a gain would mean a factor $10^{0.4\alpha_1} = 2.25$ increase in the number of $m_R \sim 23$ KBOs found and a factor $10^{0.4\alpha_2} = 1.34$ for the faintest KBOs. The true utility of an ultradeep multiyear moving object survey will depend on the actual luminosity distributions measured for the KBOs, as the luminosity distributions for faint bodies are poorly known.

2.4. Other Surveys

2.4.1. The Discovery Channel Telescope (DCT). The Discovery Channel Telescope (DCT) with a 2-deg^2 field of view will be located atop Happy Jack mountain in Arizona, a dark site with median seeing of 0.8 arcsec. With a 4.3-m-diameter primary mirror, the DCT has the ability to beat PS1 in terms of performance. However, if PS4 is delivered on time, it will likely be able to outperform the DCT. With likely DCT science beginning in 2010, about the same year PS4 science will begin, the role of DCT as a primary survey tool is somewhat diminished. If the PS4 experiment is delayed for any reason, then the DCT would be a good candidate for covering the whole sky to a fainter depth than PS1. Regardless of operation timetable, the DCT will be a useful facility for follow-up science such as the science products discussed in section 4. In particular, color measurements of the PS1 or PS4 KBOs could be a niche that the DCT could fill.

2.4.2. Visible and Infrared Survey Telescope for Astronomy (VISTA). The Visible and Infrared Survey Telescope for Astronomy (VISTA) is a 4-m telescope as well, slightly smaller than the DCT in diameter but with a larger field of view of 3 deg^2. The VISTA project is located at Cerro Paranal, and the primary mirror has already been installed, giving it the potential for being a very powerful survey telescope as it is between PS1 and PS4 in power and will be operational by 2008 or earlier. Unfortunately, the initial camera is infrared only, which is not useful for KBO discovery due to the extremely high telluric background in the infrared as well as the limited field of view (0.6 deg^2) that is typical of near-infrared cameras. There are tentative plans for a visible camera, but no firm date of delivery or funding at the present time.

For analysis of the impact of VISTA, we have split the project into two possible modes, the current near-infrared mode and a possible future visible mode upgrade. The current near-infrared mode can reach KBOs down to AB ~ 21.5 using the Y filter, the shortest wavelength (and lowest background) filter currently in the camera. Thus, the current VISTA is roughly equivalent to a 1-m telescope in the visible in terms of depth, but with only a 0.6-deg^2 field of view. Thus, the value of SP is quite close to 1 for the current VISTA project and is not considered further in this work. If a visible VISTA camera were produced, the telescope would be very powerful, with SP ~ 10. Since the schedule for such a camera is uncertain, it seems likely that the much more powerful PS4 will be available prior to a visible VISTA camera. Thus, we do not further consider VISTA in this work, although as with the DCT, a survey of KBO colors could be a useful project for VISTA.

2.5. Targeted Deep Surveys

Neither Pan-STARRS nor LSST will be able to beat existing telescopes in survey depth by large factors. Most of the deepest surveys with existing technology have already been attempted, with detections of KBOs fainter than $m_R > 27$ reported from Keck in a survey of 0.01 deg^2 by *Chiang and Brown* (1999) and from the Hubble Space Telescope (HST) in an survey of 0.02 deg^2 (*Bernstein et al.,* 2004). Both surveys found objects consistent with sky densities of ~100 KBOs per square degree near the ecliptic. A similar project could be done at Subaru using the existing 0.3-deg^2 Suprime-Cam, which could also reach $m_R \sim 27$ during a full night of excellent seeing. Thus, it seems reasonable that a project covering ~1 deg^2 to $m_R = 27$ is likely to be completed prior to the arrival of either PS4 or the LSST.

Although technology in the next decade may increase the survey area by large factors, it will not significantly increase the threshold of faintness because such research is currently aperture limited. So although deep discovery surveys have been pivotal to studying the smallest KBOs in the previous decade, in the next decade, KBO surveys are not expected to go much deeper, only wider. The LSST does propose a very

deep survey (although the specific area of which is not certain at this point), which is critical to understanding the maximum depth that could be achieved. With a ~10-deg^2 field of view, the LSST could improve on the existing sky area surveyed by a factor of ~50 or more, resulting in 10,000 very faint (m_R ~ 28) KBOs discovered. This would be a very useful determination of the faint end of the size distribution, but not impacting the entire KBO field as much as the main survey itself, which could find ~100,000 KBOs. Thus, targeted deep surveys will likely be much overshadowed by the all-sky surveys of Pan-STARRS and LSST in the coming decade (reviewed in section 4) until the advent of completely new facilities capable of breaking the m_R ~ 29 barrier, such as the James Webb Space Telescope (JWST), the Thirty-Meter Telescope (TMT), and the Extremely Large Telescope (ELT) as discussed in section 5.

3. THE NEXT DECADE OF KUIPER BELT OBJECT DISCOVERY

In this section, we outline a rough timeline of probable survey discoveries in the next decade. As each instrument comes to science production — PS1, PS4, and then the LSST — there will be two phases of discovery. The initial discovery phase will be single-lunation discovery where KBOs visible in a single month are identified. Then the very deep, processing-intensive survey can be produced after multiple years of data have been collected *only* if suitable software effort is applied. This ultradeep multiyear work would allow significant gains if the processing difficulties can be overcome. The fourth year of any of the surveys listed is the point where diminishing returns is reached since signal-to noise ratios only increase with the square root of the number of visits for the background-limited KBO surveys. We summarize the basic numbers and depth of KBO detections in Fig. 3.

3.1. Pan-STARRS PS1: 2007 to 2010

The Pan-STARRS PS1 prototype telescope is the first large-survey telescope that will come on line. Although its mirror is relatively small (1.8 m diameter, compared to 2.4 m for Sloan and 8.4 m for the LSST), the use of OTCCDs will boost Pan-STARRS' sensitivity beyond surveys with smaller telescopes such as the current generation Caltech survey (*Trujillo and Brown,* 2003). The Caltech survey uses 150-s exposures, a 1.2 m-diameter mirror, and has quite poor image quality (around 2.5 arcsec) due to the large focal plane and poor natural seeing. As discussed above, the PS1 OTCCDs will allow Pan-STARRS to perform tip/tilt correction on each chip. Actual performance should be around 0.5 arcsec on Mauna Kea and maybe around 0.6 arcsec on Haleakalā. Thus, by comparing the Caltech survey aperture (1.8 m/1.2 m), seeing (2.5 arcsec/0.6 arcsec) and typical exposure times (60 s/150 s), one can determine that the PS1 should be able to go about 1.5 mag deeper than the existing Caltech survey, achieving depths of m_R ~ 23 in about 60 s. With a field of view of 7 deg^2, the survey will cover the entire sky. In operation, the survey will likely take three 60-s exposures of each location per night. Assuming 50% of the nights are photometric, 70% of the photometric nights have seeing acceptable enough to conduct the survey, and roughly 66% efficiency due to telescope slew and image readout (30 s per location) and no observations within three days of the full Moon (75% of a lunation used), the entire survey efficiency will be about 18%. For 10-h nights, the survey could cover

$$90000\,\frac{\text{deg}^2}{\text{yr}} \approx 0.18 \times \frac{365\ \text{nts}}{\text{yr}}\,\frac{10\ \text{h}}{\text{nt}}\,\frac{20\ \text{triplets}}{\text{h}}\,\frac{7\ \text{deg}^2}{\text{triplet}} \qquad (2)$$

or the entire visible sky three times over per year (in triplets). The solar system survey will not be the only survey conducted, but if at least one-third of the allocated time is devoted to the solar system survey (a reasonable number given that solar system science is a primary goal of the experiment), it should be able to discover all the KBOs within its survey depth. For simplicity, we assume that the PS1 system will be able to survey all KBOs to m_R ~ 23 in a single year. Follow-up will occur naturally as part of the data processing pipeline as candidate objects will all have three triplets per year. In general, if subsequent visits to the same location are separated by a month, nearly all object links can be made from month to month. Multiple years will be able to add significant depth to revisits given suitable software tools, as quantified in Fig. 3 as an increase in depth with time. Note that the total object numbers computed within this document are scaled from existing surveys. Thus, when the next generation of surveys comes online and factors of ~100 to ~1000 increases in sky area surveyed are realized, population statistics are very likely to differ from expected values.

Initially, the PS1 experiment should find ~3000 KBOs, tripling the currently known sample after a year of operation, nominally by mid-2008. However, as the experiment progresses to the multiyear stage, ultradeep multiyear analysis would enable a much larger number of bodies to be found, about 7500 KBOs in total by the start of the PS4 experiment in 2010. All bodies will be automatically recovered, so the 3000 first-year KBOs will have multiyear arcs starting in mid-2008. By 2010, all the 7500 discovered KBOs will have three-year arcs. For comparison to the current KBOs population, as of this writing in the spring of 2007, 1200 KBOs are known, only 700 of which have multiyear arcs and 600 of which have three-year arcs. In terms of the KBO size distribution (for which no orbits are needed), accuracy will be increased by a factor of ~10 more objects by 2008 over the largest survey to date in terms of discovery statistics, the Deep Ecliptic Survey (DES) (*Elliot et al.,* 2005), and by a factor of ~20 by 2010. For dynamical studies, the number of "test particles" (i.e., total number of known KBOs with reliable orbits) will be increased by a factor of 2 to 10 from 2008 to 2010. It should be noted that

the full impact for dynamical studies will only be made at the third year since orbits must be well known, but limited information such as heliocentric distance and inclination data will be available for objects during the very first year of observations.

3.2. Pan-STARRS PS4: 2010 to 2014

The development and operation of PS4 will effectively mean the end of the PS1 project. Utilizing four 1.8-m mirrors on Mauna Kea instead of one on Haleakalā, the Pan-STARRS project will be able to produce a significantly deeper survey. With tip/tilt corrected seeing of 0.5 arcsec vs. 0.6 arcsec and the additional mirror area, the PS4 experiment should be able to reach about a magnitude deeper than the original PS1 experiment in the same exposure time. From Fig. 3, we see that at outset, the PS4 system will be sensitive to m_R ~ 24 KBOs, corresponding to 10,000 KBO discoveries from its first year of operation alone. By the time the LSST becomes operational in 2014, the survey depth will reach m_R ~ 24.75, resulting in 30,000 KBO detections if multiyear ultradeep detections can be made. Thus, PS4 will result in a size distribution and dynamical works using 5–10 times more objects than PS1.

3.3. Large Survey Synoptic Telescope: 2014 to 2017

Although the PS4 will likely stay operational for many years after inception for hazardous asteroid defense purposes, the advent of the LSST will take a large amount of the science interest away from PS4, at least for KBO discovery purposes. The LSST will be a significant step up from the PS4 in terms of survey power mainly due to its larger collecting area (8.4 m/four 1.8 m) and wider field of view (10 deg^2/7 deg^2). However, the LSST will suffer from somewhat poorer seeing compared to the PS4 experiment due to its use of traditional guiding (0.7 arcsec/0.5 arcsec).

Operational efficiency for the LSST is likely to be a factor of ~3 higher than Pan-STARRS. The most critically important overhead with the LSST will be the use of six filters, which will reduce sky time spent in the r filter, the most sensitive to KBOs. The current specifications for the LSST suggest that the r filter will be the most used, with 40% of visits budgeted for the r filter. The i filter, which has only slightly less sensitivity to KBOs than the r filter, will be used for 30% of visits, so together, these two filters should limit LSST efficiency to be 30% lower than PS4 after considering bandwidth differences. Due to site differences, there may be on the order of 10% more photometric nights for LSST compared to PS1 and PS4. Slew and readout overheads will also be somewhat lower for the LSST, as the main part of the survey proposes to spend roughly 9 s for telescope slew and image readout for every 30 s of on-sky exposure, yielding 77% efficiency on the sky as opposed to that of Pan-STARRS, ~66%. Thus, overall operational efficiency of the LSST will be similar to that of Pan-STARRS PS4 after accounting for filter bandwidth, readout, and site differences. One large advantage that LSST has over Pan-STARRS is that nearly all the survey time can be used to find moving objects, where for Pan-STARRS, only the fraction allocated to the solar system search will be used (approximately one-third).

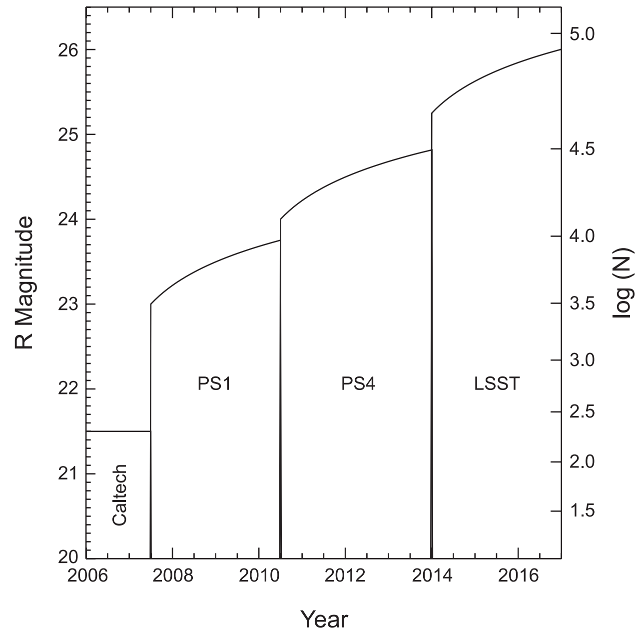

Fig. 3. Summary of the next decade of KBO all-sky survey work. Lines represent the likely survey sensitivity (left vertical axis) and the log number N of KBOs found [*Bernstein et al.* (2004), double power law model, right vertical axis] as a function of year. The three primary surveys are the Pan-STARRS PS1, the Pan-STARRS PS4, and the LSST. Also depicted is the current generation Caltech survey, the only modern all-sky survey to date with SP >1. The curved portion of each survey's coverage corresponds to increasing depth with multiple visits, and is only applicable if the survey can perform multiyear ultradeep searches for KBOs too faint for detection in a single pass.

Combining the basic instrument advantage of the LSST (in terms of SP) with the operational differences means that the LSST will be slightly deeper than the PS4 in single-visit depth, but will have a factor of ~10 more visits available, ultimately beating the PS4 experiment by about 1.25 mag in depth over similar timescale, or about m_R ~ 25.25 per year. Note that this depth assumes (as do the depths calculated for Pan-STARRS) that data collected throughout the year can be combined to find moving objects, which as described in section 2.3, is a nontrivial task. Although the LSST formally has a decade long lifecycle, we only consider the impact of the first few years in this work in our decade outlook.

The LSST may also spend ~10% of telescope time performing a very deep survey of a small portion of the ecliptic, beyond m_R ~ 27. This very deep survey will provide an additional ~10,000 very faint KBOs. This represents a few percent of the KBOs in the sky that are beyond the depth

of the primary all-sky LSST survey. The number of KBOs found in the very deep survey is very difficult to estimate as the number distribution at the faint end is currently very uncertain. As previously discussed in section 2.5, this very deep survey will provide information on some of the faintest KBOs available, but this impact will be much less than the main survey for KBO research.

The LSST's location in the southern hemisphere will allow it to identify some KBOs that cannot be seen from Hawai'i, but not a significantly large fraction. Mauna Kea is about 20° north of the equator while Cerro Pachón is about 30° south of the equator. The practical limit for reasonable survey seeing is around 1.7 airmasses, which occurs near 54° zenith angle. Thus, the PS4 survey should be able to observe as far south as –34° latitude, which will include all KBOs within about 11° of the ecliptic even near the summer opposition point. Rough estimates from the KBO latitude distribution measured by *Elliot et al.* (2005) indicate that roughly 85% of all KBOs should be northward of this limit. Thus, the only major impact that the LSST will make over PS4 due to its southern latitude will be if any particularly interesting KBOs happen to be present south of the PS4's range, such as unusually large objects.

In its first year, the LSST will detect about 50,000 KBOs, increasing the sample collected by the PS4 experiment by about a factor of 5. After a few years of operation, the LSST will be probing all-sky depths near $m_R \sim 26$. Again, if suitable moving object detection software is in place to take advantage of combining multiple years of observations, about 100,000 KBOs will be found by 2017, tripling the number of KBOs found by the PS4 experiment. Although the use of several filters lowers the LSST detection efficiency, it does allow a huge amount of color information to be gathered in the main r and i filters, as described further in section 4.7.

Overall, by the end of 2017, the additional breadth of information will be astonishing by today's standards. The total known KBO population will have increased by a factor of 80. The total number of KBOs with multiyear orbits will have increased even more dramatically, by a factor of about 150.

4. SCIENCE ENABLED BY KUIPER BELT OBJECT DISCOVERIES

The increase in knowledge over the next decade will come in sudden bursts every few years as each of the upcoming surveys are brought into science production. Between these bursts, the total number of bodies will still be growing as depth and size of the surveys increase if multiyear depth increases can be made. It is impossible to predict the science gleaned by the factor of ~100 increase in number of KBOs by 2017 compared to present-day values. However, what is clear is that certain areas of KBO research that have been stymied by lack of sample size will have many bodies available.

4.1. Luminosity Function

Measurements of the luminosity function of the KBOs will likely be the first science products to emerge from the next generation of KBO surveys. While much work has been done on the subject in the past decade, increasing the total population of KBOs by factors of ~5 every few years will dramatically reduce the random and systematic uncertainties in current estimates of the luminosity function and the associated implications for size distribution. As it now seems clear that the size distribution of bodies is not constant over the factor of ~100 range of sizes of currently observed KBOs, specific breakpoints (if they exist) can be identified and may be associated with physical or dynamical causes.

Of particular interest is the number of bodies with $m_R \sim 22$, corresponding to diameters D ~ 200 km at 45 AU. To date, a large variety of albedos have been seen in the Kuiper belt (see chapter by Stansberry et al.). What is not clear is why the very largest bodies appear to have uniformly high albedos, such as (50000) Quaoar, (136199) Eris, and (136108) 2003 EL_{61} (*Brown and Trujillo,* 2004; *Rabinowitz et al.,* 2006; *Brown et al.,* 2006). Finding a bend in the luminosity function of the bright KBOs would certainly suggest that the bright (large) KBOs could have a different albedo distribution than the medium-sized KBOs, although it is possible that this could be explained by a change in the size distribution itself as well. Such a study requires all-sky coverage to maximize counting statistics.

Also of particular interest is comparing the luminosity distribution of distinct dynamical populations. This can shed light on the possibility of unique origins for disparate classes of objects. Such a study could improve theories of separate origins for the high- and low-inclination bodies, for example.

4.2. Inclination Distribution

The inclination distribution and the ecliptic latitude distribution of bodies will be measured with extreme accuracy compared to our current state of knowledge. Although the ecliptic latitude distribution of the KBOs is known in enough detail to make rough estimates of the KBO population, this knowledge will be further refined. More interesting yet are aspects of the inclination/latitude distribution for which we have no data. The brightest bodies appear to be significantly more inclined than the fainter objects, as seen from population-averaged work as well as in initial results from the Caltech survey (*Levison and Stern,* 2001; *Trujillo and Brown,* 2003). At what point this break occurs in terms of brightness and latitude is unclear as only ecliptic surveys have the ability to find substantial numbers of faint objects and only full-sky surveys have the ability to find bright objects due to the rarity of objects. An intermediate survey that is wide enough to find significant numbers of $21 < m_R < 22$ objects is needed to explore the brightness/

inclination connection without bias. The PS1 survey fulfills just these criteria, and it is unlikely that any smaller survey will do so unless it can cover a few thousand square degrees to depths of $m_R \sim 22$.

4.3. Highly Eccentric and Distant Objects

Highly eccentric objects have extreme observational biases. In particular, Kepler's law requires objects of high eccentricity to spend most of their time near aphelion, where they are difficult to observe. Thus objects like (90377) Sedna, with an eccentricity of 0.85, are very difficult to discover since flux $f \propto R^{-4}$, where R is heliocentric distance. Thus, the ~4-mag increase from the present-day Caltech all-sky survey to the 2017 LSST all-sky survey will allow objects of similar size to be discovered at distances six times farther from the Sun than current works. Thus, bodies such as (90377) Sedna, which was found at R = 89.6 AU, and (136199) Eris, which was found at R = 97.0 AU, could be found at over R > 200 AU.

Parallactic motion at such extreme distances is very low, about 0.3 arcsec per hour, so under most observing strategies any potential objects would appear as point sources except in multiyear surveys where the ~1-arcmin-per-year orbital motion can be detected or in multinight surveys where the ~10-arcsec-per-day motion could be seen. There is no doubt that such objects are present and in significant numbers. For instance, (90377) Sedna was only detectable in the Caltech survey for about 1% of its orbit. By extrapolation, there should be many hundreds of such high-eccentricity objects that could be detected by surveys such as Pan-STARRS and LSST. There are no sound observational constraints on even more distant objects to date, so the radial distribution of objects in the 100-AU to 1000-AU distance range will be completely determined by the output of Pan-STARRS and LSST.

4.4. Small and Large Objects

Although much has been made of the recent discovery of (136199) Eris and other dwarf planets similar in size to Pluto, such discoveries could very easily become commonplace when each of the new surveys begins. Even a Mars-sized body is quite easy to hide from present-day surveys. Assuming a Mars-like albedo of 25%, and a diameter of 7000 km, a Mars-like body would be $m_R = 23$ at 300 AU, outside the range of any all-sky surveys sensitive to such objects. And of course there could be many Pluto-sized bodies at 200 AU that would be $m_R = 23$, and have remained undetected because surveys with such depths have only covered tiny fractions of the available sky, a few percent at best.

Small bodies in the Kuiper belt, those near the detection limit in terms of faintness, will make up the majority of any survey's discoveries. Thus, the greatest impact that these surveys will make, at least in number, is the vast amount of smaller KBOs. Typical sizes of interest for the surveys vary depending on the heliocentric distance at which they are found and their albedo. However, if we assume 25% albedo, and that most bodies are found at 45 AU, in the middle of the classical Kuiper belt, then PS1 will be most sensitive to diameter D ~ 100 km bodies, PS4 will be most sensitive to D ~ 50 km bodies, and the LSST will be most sensitive to D ~ 35 km bodies. The true albedo of small KBOs is unknown and is very difficult to measure. However, the approximate sizes of bodies to be discovered by the various surveys are outlined in Fig. 4 for a 25% albedo. Since body diameter is inversely proportional to the square root of albedo for a given apparent magnitude, assuming 10% albedo would result in about a 60% increase in diameter for Fig. 4.

4.5. Multiple Systems

One of the most interesting physical phenomena in the Kuiper belt is the large number of binary systems, with the possibility of increasing fractions of binaries for the larger bodies. Since most of the objects found will be near the faint limit of an individual survey, any secondaries found will likely be of similar brightness to the primary. To date, only a few binaries are known with similar brightness fractions, including the first discovered KBO binary system after Pluto/Charon, 1998 WW_{31} and its companion (*Veillet et al.,* 2002). To date, the size distribution of secondaries has not been well measured, but adding data to the equal-mass bi-

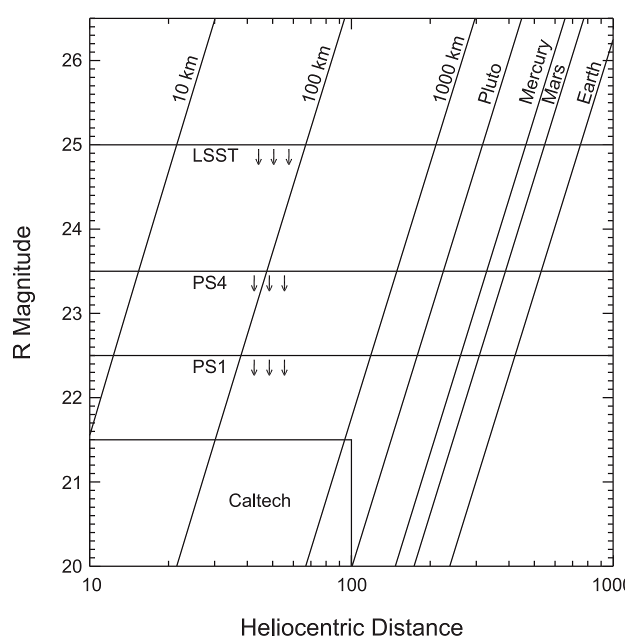

Fig. 4. Diagram of the sizes of bodies that can be detected by the current Caltech survey (rectangle in lower left) and future surveys, which enclose all observable regions below their respective horizontal lines. Due to their multiyear coverage, the future surveys have the ability to find objects at very great distances spanning a tremendous size range.

naries will likely be helpful in any future dynamical efforts studying binary production mechanisms.

4.6. Trace Populations

Some of the most interesting bodies in the Kuiper belt are the ones that are unusual in dynamical terms. For instance, the presence of high-perihelion bodies such as (90377) Sedna and others represents a population whose origins are currently being debated (*Morbidelli and Levison,* 2004; *Stern,* 2005; *Matese et al.,* 2005). Increasing the number of high-perihelion bodies by factors of 100 will add a wealth of data for comparison to dynamical models.

Other trace populations of interest are likely to be the bodies on the edge of strong Neptune resonances, which will help map the relative strength and width of the strong resonances such as the 2:3 (Pluto-Neptune) resonance. Resonances that today have only a few bodies and are not well defined will have a dramatic increase in numbers. For instance, there are about 200 bodies in 2:3 resonance, while resonances such as the 1:2, which currently only have ~20 known members, will have ~1000 or more members by 2017. Unusual objects such as 2004 XR_{190}, which has a high inclination and low eccentricity, will become much more prevalent (*Allen et al.,* 2006).

4.7. Surface Information

Very little detailed surface information will be available for most bodies due to faintness. However, once the LSST is in production with multiple color filters integrated into the survey, no additional color campaigns will be required for study. Thus the major questions found in the color surveys to date will be fed factors of 100 more data points. One potential project for either the DCT or a VISTA visible camera could be a large color survey conducted prior to the LSST. The impact of such a survey is probably best estimated after the PS1 KBOs are found, when sample sizes are known and can be weighed against telescope subscription rates and timescales for construction.

Having color information for the 50,000 LSST KBOs with $m_R < 25$ will add an unmatched amount of information to the discussion about KBO surfaces. To date, there are roughly 200 KBOs with some amount of published color information, which is a combination of many researchers' work and over 50 publications [for a compilation, see the MBOSS website (*Hainaut and Delsanti,* 2002)]. Neither PS1 nor PS4 will provide color information as only one wide filter will be used. It is likely that researchers will continue measuring colors of found bodies, but as it takes about a night of 8-m to 10-m telescope time to collect 10–20 basic colors for $m_R > 24$-mag objects, it is likely by the time the LSST arrives that no more than 1000 KBO colors will be known. Thus, during the first year of operation, the LSST will increase the number of known colors by a factor of ~50 (or a factor $\sqrt{50} \approx 7$ in signal to-noise ratio assuming Gaussian statistics) using a uniform telescope and method. This should allow the detection of many 5σ color trends that would otherwise be completely unobservable prior to the LSST. Such a large amount of color information could allow discernment of basic KBO surface types even in what are now considered trace dynamical populations, such as the weak Neptune resonances.

Such a huge amount of color information has been collected by the Sloan survey for the asteroids, which is a hint of what may be seen for the KBOs (*Ivezić et al.,* 2002). In addition, bodies with peculiarly large lightcurves, such as smaller versions of (136108) 2003 EL_{61} and (20000) Varuna, may be identified in survey data. It is completely uncertain at this point if such unusual rotators are limited to the largest KBOs. However, the PS4 and in particular the LSST with its short ~3-d visit cadence, will increase the total number of KBOs with measured photometric variability by a factor of ~500 or more over the few dozen that have currently been studied.

4.8. Fundamental Plane

Questions regarding the fundamental plane of the Kuiper belt will be easily answered with the large numbers of bodies expected as survey products. Of particular interest in this area of research will be a comparison of Kuiper belt planes for various dynamical subpopulations. It would be interesting to compare the high-perihelion bodies, for example, with the classical KBOs, to see if their different heliocentric distances have any effect on the axis about which they orbit.

5. SPECIAL SCIENCE 2015 AND BEYOND

The key areas of research a decade from now will be very different from today's. Scientists as a whole will have three very large bodies of data, collected in largely different manners. First, the basic survey data from PS1, PS4, and the LSST will provide sheer numbers of objects to study. Second, follow-up science performed at other observatories including the next generation of giant telescopes will be able to study particularly interesting objects in great detail. Third, the results of the New Horizons mission, with its Pluto-Charon encounter in 2015 and possible KBO encounters until 2020, will provide a wealth of physical data on a few selected bodies beyond 30 AU.

5.1. James Webb Space Telescope (JSWT)

The James Webb Space Telescope (JWST) will be an infrared-optimized observatory with a 6.6-m primary mirror, scheduled for launch in 2013 (*Gardner et al.,* 2006). In terms of object discovery, the JWST will be able to probe interesting areas of the Kuiper belt that will not be able to be seen from the ground. Its greatest science impact for KBO research is likely to be low-resolution spectroscopy of the faintest KBOs using the NIRSpec camera. Initial require-

ments, which are subject to change, are that the camera will be able to collect spectra with signal-to noise ratios of S/N ~ 10 for an object with m_{AB} ~ 26 in 10,000 s around 2 μm (K band). For useful KBO spectral information, one needs approximately S/N ~10 or better, requiring m_{AB} ~ 24.5, which for KBOs with mean ($m_V - m_K$) ~ 1.75 (Vega scale) requires objects brighter than m_K ~ 20 for reasonable science return. Currently, KBOs with m_K ~ 20 are very difficult to study from the largest telescopes on the ground, so this will be a factor of ~100 increase over the number of KBOs for which spectra can be collected. For the first time, spectral studies of KBOs may be more limited by telescope oversubscription rates than being limited by the small number of bright targets.

The imaging instrument NIRCam can also be used for survey work. One could target a single field for several hours and detect point sources as faint as m_{AB} ~ 28.8 in the K band, which is equivalent to about m_K ~ 25. The field of view of the detector is quite small, with only 0.0025 deg^2 covered. However, at these very faint magnitudes, which approach m_R ~29, the sky density of KBOs may be very high, a few hundred per square degree, thus one KBO will be detected for every few hours of telescope time. Such a search would not be very productive in numbers, but it would provide basic data approaching the ~10-km size regime, nearly the size of the typical cometary nucleus. A far better instrument could be the TMT, however.

5.2. Thirty Meter Telescope (TMT) and Extremely Large Telescope (ELT)

The Thirty Meter Telescope (TMT) is planned to be available for science starting around the year 2016. There are two obvious uses for the TMT in KBO surveys. The first is in the visible, where the giant collecting area can increase the depth of observation over existing telescopes in the visible, if instrumentation allows. The TMT will have a 20-arcmin field of view, covering about 0.1 deg^2 to depths of m_R ~ 29 in several hours, probing the same size range as the JWST but with factors of ~40 more objects discovered. Thus, the telescope could find some of the faintest KBOs in the visible regime. However, it is not clear yet whether the TMT will have a wide-field optical imager. It is possible that the TMT will be only equipped with near-infrared instruments due to the great performance increases that adaptive optics (AO) can provide for the near-infrared. For certain, the TMT will have a wide-field near-infrared imager, since the TMT's large size (and thus small diffraction limit of ~15 milliarcsec at 2 μm) will greatly benefit from AO correction, which generally delivers light at wavelengths longer than 1 μm. Compared to current 8-m to 10-m seeing-limited groundbased telescopes, the AO-corrected TMT will provide great advances. Sky background noise will be reduced by factors of ~4 even with the larger collecting area, since plate scales will be very fine (around 7 milliarcsec compared to 0.1 arcsec). Signal will be increased by factors of ~3.5 over current groundbased infrared instruments due to the larger collecting area. Overall, magnitudes of m_K ~ 26 (equivalent to m_R ~ 27.75) should be achievable with the TMT using AO for point sources with a few hours on source. Thus, the TMT will probably achieve sensitivities somewhat less than the JWST, but with factors of ~50 more sky area. Together, the JWST and TMT will complement one another in terms of number and size of KBOs discovered.

The largest telescope likely to be built in the next decade is the Extremely Large Telescope (ELT), under feasibility studies by the European Southern Observatory (ESO). Construction is to begin in 2010, with completion of construction in 2017. The primary mirror will be 42 m in diameter, in a segmented design. The possible instrumentation suite is still unclear, but if a visible capability is added, it should be able to break m_R ~ 29 in a few hours in seeing-limited mode. In the near-infrared, it should be able to image even fainter KBOs than the TMT, with the ability to approach m_K ~ 26.5 objects with AO correction, or m_R ~28 given typical KBO colors. The ELT will thus have access to the smallest KBOs, probably some with diameters of 5 km, those bodies that could be future cometary nuclei.

5.3. New Horizons

The science produced by New Horizons (see chapter by Weaver and Stern), which will have closest approach with Pluto in July 2015, is probably the biggest unknown for KBO science in the next decade. Although the capabilities of the instruments are quite certain, what is very poorly known is what geologic features the surface of Pluto harbors. No doubt, it will be much, much more complex than imagined from the several resolution elements across the surface that we now have. It will be very challenging to draw conclusions about KBOs as a whole from the study of Pluto/Charon and the few KBOs that may be visited in the years after the Pluto/Charon flyby. After 2015, for the first time, we will have a very deep knowledge of the largest of KBOs, and a very rudimentary knowledge of the vast population of much smaller KBOs. Connecting such depth and breadth of these disparate datasets will be the largest challenge of the next decade of KBO research.

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