Project Pan-STARRS and the Outer Solar System

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ABSTRACT

Pan-STARRS, a funded project to repeatedly survey the entire visible sky to faint limiting magnitudes ($m_R \sim 24$), will have a substantial impact on the study of the Kuiper Belt and outer solar system. We briefly review the Pan-STARRS design philosophy and sketch some of the planetary science areas in which we expect this facility to make its mark. Pan-STARRS will find $\sim$20,000 Kuiper Belt Objects within the first year of operation and will obtain accurate astrometry for all of them on a weekly or faster cycle. We expect that it will revolutionise our knowledge of the contents and dynamical structure of the outer solar system.

Subject headings: Surveys, Kuiper Belt, comets

1.   Introduction to Pan-STARRS

Project Pan-STARRS (short for Panoramic Survey Telescope and Rapid Response System) is a collaboration between the University of Hawaii's Institute for Astronomy, the MIT Lincoln Laboratory, the Maui High Performance Computer Center, and Science Applications International Corporation. The Principal Investigator for the project, for which funding started in the fall of 2002, is Nick Kaiser of the Institute for Astronomy. Operations should begin by 2007.

The science objectives of Pan-STARRS span the full range from planetary to cosmological. The instrument will conduct a survey of the solar system that is staggering in power compared to anything yet attempted. A useful measure of the raw survey power, SP, of a telescope is given by

$$SP = \frac{A\Omega}{\theta^2} \tag{1}$$

where A [m^2] is the collecting area of the telescope primary, Ω [deg^2] is the solid angle that is imaged and θ [arcsec] is the full-width at half maximum (FWHM) of the images

produced by the telescope. Equation (1) shows that large survey power demands large A and large Ω from a telescope located at a site with good seeing (small θ). Some examples of existing and planned survey telescopes are given in Table 1, where it can be seen that Pan- STARRS will be an order of magnitude more powerful than the two current leaders, the 3.6-m CFHT and 8-m Subaru telescopes (both on Mauna Kea) and two to three orders of magnitude more powerful than the currently leading asteroid survey telescopes (e.g. LIN-EAR, Spacewatch). Pan-STARRS is less powerful than the default Dark Matter Telescope design for the US National Large Synoptic Survey Telescope (DMT/LSST), but it is also cheaper, funded, and should be deep into its mission by the time DMT/LSST sees first light.

Pan-STARRS has a novel design shaped by a careful trade-off between the relative costs of the telescope, the large-format detector needed to rapidly survey the sky, and the software pipeline needed to promptly process the data. It is well known that the costs of single-aperture telescopes scale with a high power of the diameter, meaning that large telescopes (and their mounts and enclosures) are very expensive. For ground-based survey applications, where the image quality is set by atmospheric turbulence rather than by diffraction, there is no real advantage in using a single big mirror. Indeed, a more fundamental constraint is imposed on the focal length by the requirement that the focal plane be well sampled by the detector array. With a practical lower limit to pixel size near $\delta = 10$ μm and natural seeing $\theta \sim 0.6$ arcsec, Nyquist sampling requires a focal length $F = 2\delta/\theta(rad) \sim 7$-m, independent of the mirror diameter. A large diameter primary then implies a small focal ratio, making it difficult to achieve large, flat, unaberrated fields of view.

A better approach is to build up the collecting area by combining data from a number of smaller telescopes. The small telescopes can be very cheap, but detector costs rise because each telescope must be equipped with a focal plane instrument. In the case of Pan-STARRS, these and other arguments point to a design having four 'unit telescopes' each of about 1.8-m diameter, for a total collecting area equivalent to a 3.6-m diameter single mirror telescope. In addition to solving the problems of large, monolithic, short $f-$ratio mirrors, a significant advantage of this multi-aperture design is that it is infinitely scalable: an arbitrarily large collecting area can be obtained simply by adding more 'unit telescopes'. In this sense, Pan-STARRS can be envisioned as a prototype for future survey telescopes of much greater power.

The focal planes of the four telescopes will each be paved with 32k $\times$ 32k (i.e. $\sim$1 billion pixel) charge-coupled device (CCD) mosaics, with 0.3 arcsec pixel scale and a 7 deg^2 field of view. We intend to use Orthogonal Transfer CCDs (OTCCDs) in which rapid on-chip displacements of the photoelectrons can be used to achieve image stabilization and a reduction in the effective point spread function. Experiments with a 4k $\times$ 4k OTCCD on the

University of Hawaii 2.2-m telescope show that, when turned on, the OTCCD can reduce a 0.7 arcsec FWHM image to ~ 0.5 arcsec. This reduction appears small but, since the integration time needed to reach a given signal-to-noise scales as the square of the FWHM, it in fact gives a factor $(0.7/0.5)^2 \sim 2$ improvement in observing efficiency relative to a normal CCD. A further sensitivity enhancement will be obtained by using 'the Solar System Filter' which has a broad bandpass extending roughly from 5000Å to 8000Å wavelength, three times the standard broadband filter width.

The data pipeline will need to process data at rates as high as 10 Tbyte per night (this is about 300 times the data rate from our previous surveys of the Kuiper Belt at CFHT). Basic processing will include flattening, removal of the spatial distortions, and registration and combination of images from the four telescopes (each of which will point at the same spot in the sky and expose simultaneously). Objects in the data will be detected and classified based on their position, shape, and brightness and then placed into one of several dynamic object databases, including a moving object database that will include everything in the solar system, from Near Earth Objects to Kuiper Belt Objects and beyond.

2. Outer Solar System Survey (OSSS)

The OSSS aims to detect and obtain repeated high quality astrometry on every accessible solar system object brighter than red magnitude $m_R = 24$. If we take the accessible sky area to be 3/4 of 4π steradians, including the entire ecliptic down to declinations about -40 deg, then the 7 deg^2 field of view of Pan-STARRS requires $\sim$4000 pointings to cover the sky. At 30 sec per pointing to reach $m_R = 24$, this will take about 40 hours (4 nights). A detailed cadence strategy has yet to be defined based on optimization of the disparate science requirements, but it is clear that Pan-STARRS has the capacity to provide several revisits to each OSSS target every month, and several dozen revisits per year. This should provide a truly fabulous catalog of orbits of outer solar system bodies, as we now discuss.

2.1. Trojan Objects

Jupiter maintains a large population of Trojans (bodies sharing Jupiter's orbit but circulating $\pm$ 60 deg. from the planet in longitude at the L4 and L5 Lagrangian points). More than 1600 are known as of May 2003 but the total population is far larger. When measured down to diameters $D \sim 1$ km, the number of Jovian Trojans is of order 6×10^5 (Jewitt et al. 2000), comparable to the number of $D \geq 1$ km main-belt asteroids. Pan-

STARRS will find the $\sim 10^5$ Jovian Trojans that have $m_R < 24$ and determine accurate orbits for each. This much enlarged sample is expected to form the basis for a greatly improved understanding of these bodies. The long standing question as to whether the $L4$ and $L5$ swarms are differently populated should be definitively answered. Dynamical families, to date only glimpsed, should become well defined. Since the survey covers most of the sky, the distributions of inclination and libration amplitude will be determined relatively free of the observational bias effects that afflict present determinations. The size distribution will be measured for a complete sample that brackets the collisional rollover at $H \sim 11$.

Most importantly, Pan-STARRS will accumulate equivalent data on the Trojan clouds of the other giant planets, all of which have the potential to retain Trojans (Nesvorny and Dones 2002). A single Neptunian Trojan is currently known. Table 2 lists the numbers of Trojans that would be seen at $m_R < 24$ if each planet held a population of Trojans like that of Jupiter. Since the relative stabilities of orbits at the different planets are not equal, this is unlikely to be a particularly accurate estimate of the Trojan populations. Nevertheless, the numbers are impressive: we expect to find large numbers of Trojans of the outer planets if they exist.

2.2. Comets

The comets are usefully divided into groups based on the Tisserand parameter measured with respect to Jupiter, defined by

$$T_J = \frac{a_J}{a} + 2 \left((1 - e^2) \frac{a}{a_J} \right)^{1/2} cos(i) \qquad (2)$$

where $a_J = 5.2$ AU is the semi-major axis of Jupiter's orbit and a, e and i are the semi-major axis, eccentricity and inclination of the comet (Levison 1996).

The currently known comet sample is highly biased towards objects with small perihelion distances and these tend to include a disproportionate fraction of Jupiter Family Comets (JFCs: objects with $2 \leq T_J \leq 3$). Perihelion bias causes the JFCs to be over-represented compared to the long period comets (LPCs) and Halley Family Comets (HFCs) both of which have $T_J \leq 2$. The LPCs and HFCs have larger perihelia, on average, and are therefore fainter and more difficult to detect. For example, while only a few dozen HFC comets are known (compared to hundreds of JFCs), it is suspected that the HFC population could rival or exceed that of the JFCs.

The deep, all-sky imaging provided by Pan-STARRS will allow us to reduce the effects

of observational bias, leading to a better determination of the relative sizes of the cometary subclasses and so of their source reservoirs. Unfortunately, estimating the numbers of comets to be found by Pan-STARRS is extremely difficult. One important reason is that we do not understand the controlling factors behind the apparent brightness of a comet. Mantling, in particular, modulates the mass loss rate and total brightness in a profound way but is not quantitatively understood: we don't know how mantling varies with nucleus size or age. Another is that the comets are diffuse objects and it is difficult to know what has been measured when a cometary magnitude is reported. Detection and discovery of comets at large heliocentric distance will minimize the problem of cometary magnitude measurements.

The present rate of discovery of comets of all types (neglecting SOHO discoveries of sungrazers) is about 40 yr^{-1}, with most found by the LINEAR and NEAT asteroid survey telescopes. A reasonable guess is that Pan-STARRS will find at least 10 times as many per year, corresponding to a few $\times\ 10^3$ in 10 yrs of Pan-STARRS operation. Most of these will be faint comets with large perihelia and membership in non-JFC families that are as-yet poorly probed.

2.3. Centaurs

The Centaurs are likely Kuiper Belt escapees that are strongly interacting with the giant planets (perihelia fall in the $5 \le q \le 30$ AU region). The extrapolated Centaur luminosity function reaches a cumulative surface density $\sim 0.4\ \mathrm{deg}^{-2}$ at $m_R = 24$ (Sheppard et al. 2000). In an all-sky survey with Pan-STARRS we expect to find of order 10^3 Centaurs with $m_R \le 24$. This represents a large increase relative to the $\sim$50 currently known Centaurs. Their main scientific value lies in their use as closer, brighter proxies of the Kuiper Belt Objects. Many of them are also destined to become mass-losing comets once they are scattered inside the orbit of Jupiter. Identification of a large sample will motivate intense study of the dynamical and physical properties of these interesting, dynamically intermediate objects. Discovery of Centaurs will also result in a sample of "pristine" JFCs prior to their entry into the JFC population.

2.4. Kuiper Belt Objects

A major use of Pan-STARRS will be to extend initial investigations of the Kuiper Belt via an all-sky survey to $m_R \sim 24$. The special advantages of Pan-STARRS for Kuiper Belt science are two-fold.

First, the observing cadence will be determined largely by fast-moving Near-Earth Objects, which must be observed at short intervals in order to provide orbital linkage between separated nights. This means that we will obtain more than enough repeated astrometry of the slow-moving KBOs for their orbits to be reliably determined in all cases. Pan- STARRS will not lose the KBOs it finds. The quality of the astrometry will also be very high, starting at $1\sigma = 200$ mas in the beginning of the project and shrinking towards 50 mas as the astrometric grid self-improves.

Second, the Pan-STARRS survey will be more nearly free of many of the observational biases that afflict published work (such as uneven sampling of ecliptic latitude and longitude, preferential follow-up of bright KBOs), allowing confident determination of the dynamical structure from a well-characterized sample of KBOs.

Amongst the issues to be addressed from such a survey are

- **The Inclination Distribution** The inclination distribution is a measure of the internal velocity dispersion in the Belt, and hence determines the energy and frequency of collisions among KBOs. We already know that the apparent half width of the inclination distribution is $i_{1/2} \sim 5$ deg (Jewitt et al. 1996). However, existing data are strongly biased against high inclination objects and the true width may be $i_{1/2} \sim 20$ deg or even larger (Trujillo et al. 2001). This width corresponds to a velocity dispersion among KBOs $\Delta V \sim 1.5$ km s^{-1}. If the Kuiper Belt were an undisturbed accretion disk, we would expect $i_{1/2} \sim 1$ deg (Holman and Wisdom 1993) and $\Delta V \sim 0.1$ kms^{-1}. Clearly, the Kuiper Belt has been dynamically excited since the accretion epoch. But how? Suggested agents include scattering by massive planetesimals, excitation by sweeping resonances, mutual scattering in a dense early phase and tidal excitation by a passing star. The different models present testable implications for the variation of inclination with distance and with dynamical regime in the Kuiper Belt. A large sample of KBOs with well-determined orbital elements is needed to begin to distinguish amongst these models. Pan-STARRS will be sensitive to KBOs at all ecliptic latitudes, reducing the inclination bias to nearly zero.

- **The Sky-Plane Distribution** Perturbations by Neptune impose azimuthal and inclination structure on the Kuiper Belt, particularly on those objects trapped in mean-motion resonances (Malhotra 1996). For example, the 3 : 2 resonant Plutinos have perihelia clustered near ± 90 deg from Neptune's longitude and, in a magnitude limited survey, will be preferentially detected at these longitudes. The 2 : 1 resonant "Twotinos" cluster near ± 75 deg (Chiang and Jordan 2002). In a magnitude-limited survey, the sky-plane distribution can be used to infer important properties of the

trapping. As one example, the number of Twotinos leading and trailing Neptune pro-
vides a powerful constraint on the migration history of the orbit of this planet (Chiang
and Jordan 2002; c.f. Figure 1). Few Twotinos are presently known: we expect to
find hundreds with Pan- STARRS, sufficient to analyse the predicted asymmetries and
population ratios.

- **Dynamical Structure** The known KBOs fall into a few broad dynamical categories,
  including the so-called Classical, Resonant and Scattered KBOs, each with different
  histories and different implications for processes occuring in the early solar system.
  Other sub-types may await discovery in a large, uniform survey of the sky, and we may
  be able to identify families produced by collisions, from which some of the collisional
  history of the Kuiper Belt might be disentangled (Chiang 2002). The properties of
  the sub-types remain poorly known, largely because of observational bias. A major
  problem has been with astrometric follow-up: objects with uncertain or peculiar orbital
  elements might be more likely to escape follow-up, leading to an implicit bias against
  such objects. Pan- STARRS will be the first survey to provide complete follow-up
  of every detected object. The total number of KBOs to be found in the survey is $\sim$
  20,000, based on the measured luminosity function (Trujillo et al. 2001).

- **Other Plutos** Pluto is the largest known KBO. It was detected first presumably
  because it is the only 2000 km scale body trapped in the 3 : 2 resonance at the
  relatively small semimajor axis $a = 39.4$ AU. Other Pluto-sized objects could exist in
  more distant resonances, or be far away members of the Scattered Disk. If removed
  to $R = 300$ AU, Pluto would appear at $m_R \sim 24$ and could just be detected in the
  Pan- STARRS survey. Some growth models indeed suggest that accretional runaway
  should produce more than one Pluto sized object (Kenyon and Luu 1999) and a search
  for these objects seems worthwhile. It is interesting to speculate as to whether other
  2000 km scale KBOs must necessarily be high albedo ($p_R \sim 0.6$) objects like Pluto, or
  might there be 'dark Plutos' with albedos more similar to those measured for Varuna
  and Quaoar ($p_R \sim 0.06$ - 0.10)? A dark Pluto ($p_R \sim 0.06$) could be detected by
  Pan-STARRS only to $R \sim 170$ AU.

- **Wide Binaries** Several KBO binaries (Pluto, angular separation $\delta\theta = 0.9$ arcsec),
  1998 WW31 ($\delta\theta = 1.2$ arcsec) and 2001 QW322 ($\delta\theta = 4.0$ arcsec) can be resolved into
  separate components under typical Mauna Kea seeing. The implied fraction of wide bi-
  naries (3 objects out of $\sim$750 known) corresponds to about 0.4%. In a sample of 20,000
  KBOs, we therefore predict $\sim$80 wide binaries. Continued Pan- STARRS observations
  will define the orbit periods (expected to be $\sim$1 yr) and supporting data from space
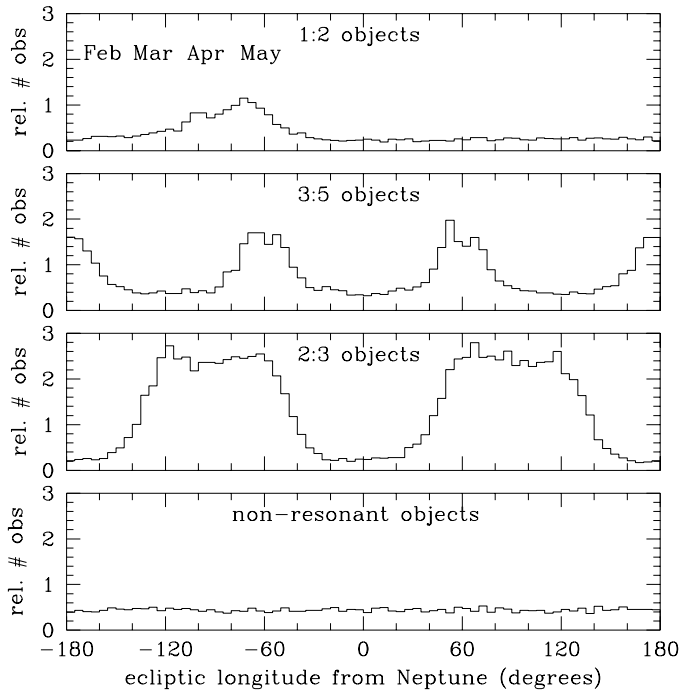 telescopes and/or adaptive optics equipped ground-based telescopes will provide accu-

Fig. 1.— Predicted azimuthal variation of the surface density of KBOs including Twotinos (top panel), 3 : 5 resonance objects (2nd panel down), Plutinos (3rd panel down) and non-resonant objects (bottom panel). The clustering of the perihelia of the resonant objects results in their preferential detection in certain directions by magnitude limited surveys. The azimuthal variation, in particular the east-west asymmetry relative to Neptune seen in the Twotinos, depends on and may allow us to measure the migration timescale. This, in turn, is related to the growth time of Neptune. Figure kindly provided by Matt Holman, CFA.

rate semimajor axes from which system masses can be deduced. Production of a large sample of wide binaries will place strong constraints on the time-integrated collisional environment in the Kuiper Belt, as well as on the binary formation mechanism.

2.5. Interstellar Interlopers

Planet formation is a dirty process that leads to the pollution of the interstellar medium with processed debris from the protoplanetary disks of young stars. Macroscopic objects from the disk are ejected to interstellar space by strong gravitational interactions with growing planets. For example, it is thought that the $\sim 10^{12}$ comets of kilometer size now in the Oort Cloud are merely the trapped members of a set of at least 10^{13} similar objects that were expelled from the solar system (primarily by the giant planets; Hahn and Malhotra 1999). Other stars presumably also ejected disk debris, meaning that we might detect interstellar debris from other planetary systems that wanders by chance near the Sun.

No such objects, which would be observationally distinguished by their strongly hyperbolic (unbound) orbits, have ever been reported. Sadly, it is difficult to turn this nondetection into a quantitative limit on the allowable density of interstellar comets because the relevant surveys have been, until recently, visual or photographic and hard to characterize (c.f. Sekanina 1976).

A simple estimate of the rate at which interstellar interlopers pass by is

$$dN/dt \sim f\pi N_1 R_c^2 \Delta V, \tag{3}$$

where N_1 is the number density, R_c is the limiting distance within which an object must pass to be detected, $\Delta V \sim 20$ km/s is the relative velocity and $f \sim 1$ is the gravitational focussing parameter. For a low albedo, comet-like body of radius r, the limiting distance is $R_c \sim 5$ AU $(r/1\ km)^{1/2}$. For reference, suppose that each of the 10^{11} stars in the galaxy, like the Sun, ejected 10^{13} comets having radius $r \geq 1$ km. Then the density of interstellar comets larger than 1 km would be 10^{13} times that of the stars, or $N_1 \sim 10^{-3}$ AU^{-3}. Substituting gives a nominal encounter rate $dN/dt \sim 0.3$ yr^{-1} for $r \geq 1$ km objects. The implication is that we will either detect a few interstellar interlopers over the nominal 10 year lifetime of the survey or place interesting limits on their number density. The limits become stronger if the interstellar debris size distribution extends substantially below 1 km and if the differential size distribution is steeper than $r^{-5/2}$.

2.6.   Unseen Companions to the Sun

Unseen companions to the Sun, including planets and substellar objects, may exist in the outer solar system. The Oort Cloud and the Scattered Disk are testament to an early phase in which the growing planets scattered objects to large distances. Conceivably, Earth-sized or even larger bodies could have been scattered into distant regions of the solar system. The Sun could even be a member of a wide binary system, with the other component being of low luminosity or substellar in mass. Limits to the mass of such companions have been set from the absence of measurable gravitational perturbations on the known planets, and are approximately given by (Hogg et al. 1991)

$$M \lesssim (6 - 10) \left[\frac{R}{100AU} \right]^3 M_\oplus, \tag{4}$$

where $M_\oplus = 6 \times 10^{24}$ kg is the mass of the Earth. We are interested in the limits that can be set optically, using Pan- STARRS. For a given apparent magnitude, the radius, r, and distance, R, of an object viewed in scattered light are related through $r \propto R^2$. With mass $M \propto r^3$, the optical counterpart to Eq. (4) gives $M \propto R^6$. Despite this very steep distance dependence, optical detection can provide more sensitive limits to distant planets than can those offered by Eq. (4). For Earth, Jupiter, Neptune and Pluto, Table 3 lists R_{24}, the distance at which the visual apparent magnitude reaches the Pan-STARRS limit. Also listed is R_{grav}, the distance inside which the gravitational perturbations due to each planet should become detectable (as computed from Eq. (4)). For each case we see that $R_{24} > R_{grav}$, showing that Pan-STARRS will improve on the existing limits to distant planets based on the absence of measurable perturbations.

The detectability of low mass brown dwarf companions will be like that of Jupiter (i.e. visible at ∼2000 AU), since cold degenerate bodies are all of similar size and emit no visible light. More massive, hotter substellar objects emit at the reddest optical wavelengths and can be detected throughout the Sun's Hill sphere. Indeed, the Pan-STARRS '3π' survey aims to catalog and obtain parallaxes for all low mass objects to ∼10 pc within the first year of operation.

3.   Scientific Impact of Pan-STARRS

A short summary of the likely solar system products of Pan-STARRS is given in Table 4. The projected 1-year discovery numbers are all uncertain, in the best cases (e.g. Jovian Trojans, Kuiper Belt) by a factor of a few, in the worst cases (e.g. Trojans of other giant

planets, comets, interlopers) by order of magnitude. Still, it is reasonable to conclude from Table 4 that Pan-STARRS will quickly push the study of the outer solar system into a new and uncharted realm.

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Table 1: Survey Power of Telescopes

Telescope	D [m][a]	A [m²][b]	Ω [deg²][c]	θ [arcsec][d]	SP[e]	Status
LINEAR[f]	1.0	0.8	2	2.5	0.2	Active
Spacewatch	0.9	0.6	3	1.5	0.8	Active
UH 2.2-m/PFCam	2.2	3.5	0.25	0.7	1.8	2004+
Palomar/QUEST	1.2	1.1	16.6	2	4.6	2003+
CFHT/Megacam	3.6	10	1.00	0.6	28	Active
Subaru/Suprimecam	8.0	45	0.25	0.6	35	Active
Pan-STARRS	3.6	10	7	0.5	280	2007+
DMT/LSST	8.3	54	7	0.6	1050	2012+

[a]Telescope diameter

[b]Effective collecting area

[c]Solid angle subtended by field of view

[d]Nominal image quality

[e]The survey power, in units [m² deg² arcsec⁻²], defined by Equation (1)

[f]LINEAR has recently been using two similar telescopes, raising the survey power to 0.4 m² deg² arcsec⁻²

Table 2: Trojan Population Scaling

Planet	Semi-axis [AU]	Δm [mag][a]	N($m_R < 24$)[b]
Jupiter	5.2	0	100,000
Saturn	9.5	2.8	8,000
Uranus	19.6	6.2	350
Neptune	30.0	8.0	50

[a]The magnitude decrement incurred in moving from Jupiter to a more distant planet.

[b]Number of Jovian Trojans that would be detectable in a survey to $m_R = 24$, if displaced to the greater distances of the outer planets.

Table 3: Detectability of Distant Planets

Planet	V(1,1,0)[a]	R_{24} [AU][b]	R_{grav} [AU][c]
Earth	-3.9	620	50
Jupiter	-9.3	2140	340
Neptune	-6.9	1230	130
Pluto	-1.0	320	N/A

[a]Absolute magnitude of the planet, equal to the V magnitude at unit heliocentric and geocentric distance and zero phase angle

[b]The distance at which the planet would have apparent magnitude $m_V = 24$.

[c]The distance at which the gravitational perturbation by the planet would just be detectable, as computed using Eq. 4. Pluto is undetectable by this method at any distance for which Eq. 4 is valid: See Hogg et al. 1991.

Table 4: Pan-STARRS Solar System

Object Type	N(now)[a]	N(1 yr)[b]
Jovian Trojans	1600	~100,000
Kuiper Belt Objects	750	~20,000
Trojans of Other Giant Planets	1	~10,000?
Centaurs	~50	~1,000
Comets (all types)	~1,000	~400?[c]
Wide KBO Binaries	3	~100
Interstellar Interlopers	0	~1
Companions	0	?

[a]Number of objects of each type currently (mid 2003) known

[b]Number of objects expected after 1 year of Pan- STARRS operations. All projected numbers are uncertain, at least by factors of a few, in some cases by order of magnitude

[c]Total number found will increase with the duration of the survey