SCIENCE OVERVIEW

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Abstract. Pan STARRS will be unique in its ability to simultaneously satisfy a large number of different science programs on subjects ranging from the nearest asteroids to the most distant galaxies. Here, we present an overview of the science case for Pan STARRS.

1 Background

Ever since the time of Tycho Brahe, carefully planned surveys of the sky have played a defining role in shaping our view of the universe. As technology developed, we have moved from using the human eye as the primary sensor, to the photographic plate and, only recently, to the use of large-format digital detectors having vast numbers of pixels. A result of this move towards wholly digital data is the near total reliance on computers, both to obtain the electronic images and to extract from them measurements of scientific value. The "state of the art" in astronomical surveying technology therefore lies at the intersection between optics (in design of wide-field telescopes), solid state physics (large format imagers) and raw computing power (to acquire and process the data).

Of the numerous on-going digital surveys of the sky, we single out for comparison the Sloan Digital Sky Survey (SDSS) which drift-scans ~100 deg^2 per hour to magnitude $m_R \sim 22.5$ in pursuit of numerous galactic and extragalactic science objectives and the United States Air Force LINEAR project, which surveys ~600 deg^2 per night to $m_R \sim 19.2$, with Near Earth Objects (NEOs) as the principal targets (Stokes et al. 2003). The peak data rates of these surveys are near a few 10's of Gbyte per hr. These and other surveys provide the background and context for project Pan STARRS, which will have sky coverage near 6000 deg^2 per night to $m_R = 24$, a data rate anticipated to be near 1 Tbyte per hr and which will be much more powerful for surveys than SDSS and LINEAR combined. Pan STARRS is sufficiently powerful to be able to obtain repeated coverage of the whole sky on timescales of less than a week, sufficiently short to reveal many new astrophysical phenomena and, in essence, to make a digital movie of the whole sky reaching down to 24th magnitude in a single frame. We expect that Pan STARRS will open a new window on all-sky, optical "time domain" astrophysics, with exciting applications extending from the nearest asteroids and comets to the most distant supernovae and gamma ray burster afterglows.

A simple measure of the expected performance of Pan STARRS relative to existing telescopes is provided by the product of the telescope collecting area, A (m^2), with the solid angle viewed, Ω (deg^2). This quantity is listed in Table 1.

Table 1. Relative Performance of Various Telescopes

Telescope	Diam. (m)	Ω (deg^2)	AΩ
USAF LINEAR	1.0	2.0	1.5
SDSS	2.5	3.9	6.0
CFHT Megacam	3.6	1	8.0
Subaru SuprimeCam	8.1	0.2	8.8
Pan STARRS	3.6	7	60
Nominal LSST	6.5	7	190

1.1 Relation to Large Synoptic Survey Telescope (LSST)

The LSST is a $170M wide field survey project recommended by the McKee-Taylor 'Decadal Review of Astrophysics' in 2000. Implementation of LSST has been taken up as a primary mission of NOAO. Pan STARRS is specifically not intended to be the LSST: this is obvious in Table 1 where the AΩ product for Pan STARRS is seen to be about one third of that envisioned for LSST. Nevertheless, we expect that Pan STARRS will accomplish many of the science objectives of the LSST and will do so on a comparatively short timescale. We consider Pan STARRS as a prototype for LSST.

2 Pan STARRS Science Overview

The science cases that motivate the Pan STARRS project are given in the Appendices to this proposal, to which the reader is referred. In this section we provide an overview of the key science, focussing on projects that drive either the design of the telescope, the pipeline processing requirements, the survey operation mode or some combination of these important factors. There is in addition a large body of science that is more 'parasitical', in the sense that it does not drive the Pan STARRS design but can be obtained from observations taken for another project. These science projects, no less valuable than the ones emphasized here, are also described in the Appendices.

The key attributes of Pan STARRS relative to other surveys are

- The large AΩ, greater than the sum of all survey telescopes yet built.
- The repeated all-sky coverage, with cadence tailored to the optimal detection of moving and transient objects.
- Real-time pipeline processing of the data and dissemination to the astronomical and public/educational communities.

The science proposals attempt to capitalize on these attributes. For convenience, we have labelled the science areas as follows:

- **AGN** Active Galactic Nuclei
- **EGGS** Extragalactic and Galactic Stellar Science
- **EXO** Exoplanets
- **FIS** Far Infrared Sources
- **GRB** Gamma Ray Bursters (and afterglows thereof)
- **KBO** Kuiper Belt Objects
- **LSB** Low Surface Brightness and Dwarf Galaxies
- **LSS** Large Scale Structure
- **MBA** Main-Belt Asteroids (and other asteroid science)
- **NEO** Near Earth Object Threat
- **OSS** Other Solar System Science
- **SNE** Supernovae (as cosmological probes)
- **SOL** Solar Neighborhood
- **SPH** Spheroid Formation
- **VAR** Variability Science (especially stellar)
- **WL** Weak Gravitational Lensing
- **YSO** Stars (especially star formation studies)

2.1 Moving Object Science (EGGS, KBO, MBA, NEO, OSS, SOL)

Repeated imaging of the sky provides sensitivity to moving objects, on which a number of Solar System and stellar science cases are predicated. The Solar System applications are divided into two groups.

- **Near Earth Objects (NEO)** Pan STARRS will provide unprecedented sensitivity to small NEOs, particularly those whose orbits bring them within MOIDs (Minimum Orbit Intersection Distances) of 0.05 AU or less and which therefore constitute a potential impact threat to Earth. Interest in the NEO threat is widespread, and programs underway (dominated by LINEAR) aim to find 90% of the NEOs larger than 1 km within about a decade. These large objects dominate the impact fatality rate because they induce global scale catastrophes, including the shutting down of photosynthesis. Smaller objects, while not capable of wiping out civilization, can nevertheless inflict severe local or regional damage. Pan STARRS will detect asteroids with substantial efficiency down to 300-m scales by concentrating its search near the ecliptic and at "sweet spots" ahead of, and behind, the Earth's motion (Figure 1).

- **Outer Solar System (OSS, KBO)** The second group of Solar System applications concerns the study of other small-body populations, principally those at large distances from the Sun. Included are the Kuiper Belt Objects (KBOs, these have semimajor axes greater than Neptune's $a_N = 30$ AU), Centaurs (defined as having perihelia between Jupiter's orbit at $a_J = 5.2$ AU

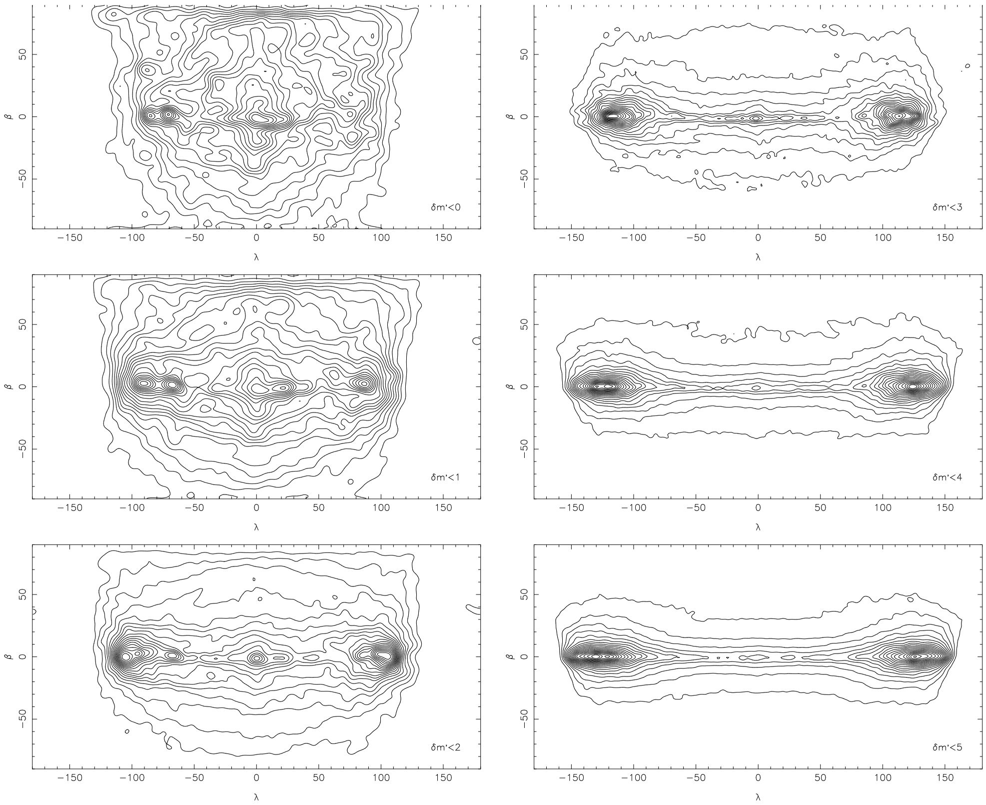

Fig. 1. Density of NEOs detectable at various thresholds, δm, weighted by their collision risk. Here β is the ecliptic latitude, and λ is ecliptic longitude measured from $\lambda = 0$ at the opposition point. The contours are evenly spaced. The sweet-spots show a high density of large objects (large δm), though there is also a high density along the ecliptic passing through the opposition point. For small objects the risk density is much more spread out across the sky.

and a_N, and representing recently escaped KBOs), Trojans (bodies in 1:1 mean motion resonance with the planets) and comets (planetesimals with high volatile contents). Most of these objects are distinguished by having thermal histories that are benign: they are widely thought to contain the most primitive, least processed material in the solar system and therefore to provide our most direct links to the processes of accretion and planet growth in the primordial solar nebula. Pan STARRS will revolutionize the study of these bodies by determining the population characteristics (Table 2).

We illustrate the kinds of science that will be enabled by considering the Kuiper Belt, although similar benefits will accrue to the other small-body populations. In the Kuiper Belt, Pan STARRS will detect ∼20,000 objects and provide ever-improving orbits for them through the lifetime of the telescope. The sample will be all-sky and therefore free of observational bias

Table 2. Small Body Populations

Class	Now Known	Pan STARRS
Jupiter Family Comets	∼140	1000?
KBOs	∼700	20,000
Centaurs	∼50	1,000
Jovian Trojans	∼1500	10^5
Main Belt Asteroids	$\sim 10^5$	$5{\times}10^6$

against high inclination objects. Accurate, unbiased orbits of such a large sample will allow us to study Kuiper Belt dynamical structure in exquisite detail, much as we now can study the main-belt asteroids. With $m_R \leq 24$, most Pan STARRS KBOs will be amenable to physical follow-up observations with large telescopes. Based on existing data and an inference from the model of binary formation by dynamical friction, we expect that several dozen to ∼100 of the KBOs will be resolved pairs with separations > 0.7 arcsec. Repeated visits will establish the orbital motions for these binaries, leading to estimates of their mass. Repeated photometry will also determine the shape and rotation period vs. size relations. For larger bodies we expect that these quantities are primordial but, below some critical size, we should expect to see the effects of more recent collisional processing.

- **Parallaxes (SOL)** Solar System objects are not the only moving targets for Pan STARRS. In the first year of operation we will build an all-sky catalog of parallaxes out to ∼10 pc. Over the 10 year duration of the project, this catalog will expand to provide parallaxes and proper motions to all objects within ∼100 pc. This will become the fundamental database for the local stellar luminosity function. Sensitivity to low-temperature, substellar objects will be obtained by using, in addition to standard R and I filters, full-sky coverage in Z ($\lambda \sim 0.9\mu$m) and Y ($\lambda \sim 1.0\mu$m). In this way, Pan STARRS will outclass some surveys conducted using near infrared detectors (e.g. UKIDSS), being complete for T dwarfs out to ∼50 pc. The resulting large, volume-limited sample of brown dwarfs will be used to constrain the substellar IMF (Initial Mass Function) in the solar vicinity. Repeated observations may also show photometric variability associated with brown dwarf "weather", and will reveal how this weather varies with spectral type. The brown dwarf sample will be 1 to 2 orders of magnitude larger than provided by either SDSS or 2MASS.

- **Proper Motions (EGGS)** On the 10 yr timescale envisioned for Pan STARRS, proper motions will be detected for most of the stars in the galaxy. At 1 kpc, the proper motion measurements in 10 yrs will be equivalent to sky-plane velocity errors $\sim \pm$ 2.5 km s^{-1}, more than adequate for the identification of mass streams in halo stars that might indicate accretion of satellite galaxies. While not a driver of the Pan STARRS design or strategy, obtaining and maintaining a highly accurate astrometric database for millions of stars does impact the pipeline design requirements. Proper motions studies for $\sim 10^8$ stars will surely impact our understanding of the structure of our galaxy.

Pan STARRS data will provide the tie to a more distant, immobile astrometric frame. In the course of the astrometric studies, Pan STARRS will establish the de facto faint object astrometric reference catalog, fully tied in to the higher accuracy but comparatively sparse catalogs based on bright stars (e.g. Hipparcos and, later, GAIA).

2.2 Static and Invariable Object Science (EGGS, SPH, FIS, LSB, LSS, WL)

- **Weak Gravitational Lensing (WL)**
  Weak lensing measurements provide a unique probe of the mass distribution in the Universe. Pan-STARRS will be able to obtain precise measurements of the power-spectrum of mass fluctuations at low redshift, and over sufficiently large scales that the results can be directly compared to measurements of the power-spectrum at high redshift from microwave background anisotropies.

  The optimal strategy for these observations is to survey the largest solid angle that is practical, and to combine a very large number of short observations, in order to control systematics. The ultimate goal of these studies is to constrain cosmological parameters and theories of cosmological structure formation. Weak lensing measurements will be made on the accumulated images of the static sky.

  What is the low-redshift power-spectrum of mass fluctuations? Observations to a detection limit of $R \sim 26$ (5-σ, point source) probe galaxies at typical redshift $z \sim 1$ and therefore are most sensitive to the mass fluctuations at $z \sim 0.4$. Current measurements are noisy, and limited to small scales. It is of great importance to extend these measurements to larger angular scales where one can compare directly with perturbations of the same scale at $z \sim 1000$ as deduced from cosmic microwave background anisotropies. Also of interest is the shape of the power spectrum; does it show the turnover at large scales predicted by theory?

  What is the relation between the clustering of galaxies and the clustering of mass on large scales? Comparing the cross-correlation of galaxies and mass with the galaxy- or mass- auto-correlation function tells one directly how the galaxies are ‘biased’ with respect to the mass. On smaller-scales galaxy-galaxy lensing can tell one the mean dark matter halo profile of galaxies as a function of luminosity and galaxy type and also how the halos have evolved with time.

- **Large Scale Structure (LSS)**
  Studies of the clustering and spectral evolution of galaxies have the potential to identify and characterize the physical processes that drive the formation and evolution of structure within our Universe. In fact one of the strongest constraints on the models for structure formation is that the theoretical models predict a strong differential clustering signal as a function of galaxy type and absolute magnitude. Standard Cold Dark Matter (CDM) cosmologies predict that the clustering evolution of halos is dependent on mass; more massive halos evolve less rapidly than lower mass halos. By quantifying how the clustering and densities of different populations evolve, we can we can understand the relation between the luminosity and mass of galaxies (i.e. we probe the biasing of galaxies).

  With Pan STARRS we can study the evolution of galaxies over the widest possible range, using deep multi-band imaging (e.g. $m_R = 27.5$, $m_Z = 25.3$) over 1200 deg^2 of sky. With these data, the two-point correlation function and power spectrum of galaxies will be determined as a function of redshift (determined photometrically) over a substantial patch of sky. Results will include measurements of the evolution of clustering and the distribution of mass to $z \sim 1.5$.

- **Formation and evolution of galaxies and AGN** (LSBs, AGN, SPH)
  The synergy between the wide field, medium deep, and ultra deep surveys will enable studies of galaxy formation and evolution from nearby dark matter dominated dwarf spheroidals to quasars and radio galaxies at $z \sim 7$. Together these surveys will probe several major transitions in the history of the universe: the epoch of reionization, the epoch of metal formation in the IGM, the epoch of spheroid formation, the epoch of peak AGN activity, and the subsequent decline of AGN to a population of dark supermassive black holes in the centers of most galaxies today. PanSTARRs will determing the comoving number density of L_* ellipticals ($z > 2$) to discrimate between competing theories for the formation of spheroids, and find the most distant galaxies and quasars in the universe.

2.3 Transient and Variable Object Science (AGN, EGGS, EXO, GRB, SNE, SOL, YSO, VAR)

Pan STARRS will detect several $\times 10^8$ variable stars in our galaxy alone and a larger number of variable extragalactic objects (c.f. Figure 3). Again, the full range of applications from solar system to cosmological is naturally provided.

- **Supernovae (SNE)** The report of evidence for a positive cosmological constant from Supernova redshift data is one of the more astounding astronomical results of the last decade (c.f. Figure 4, from Tonry et al. 2003). The strength of this detection, aside from systematic effects that are being addressed independently, rests on statistical uncertainties that must be reduced

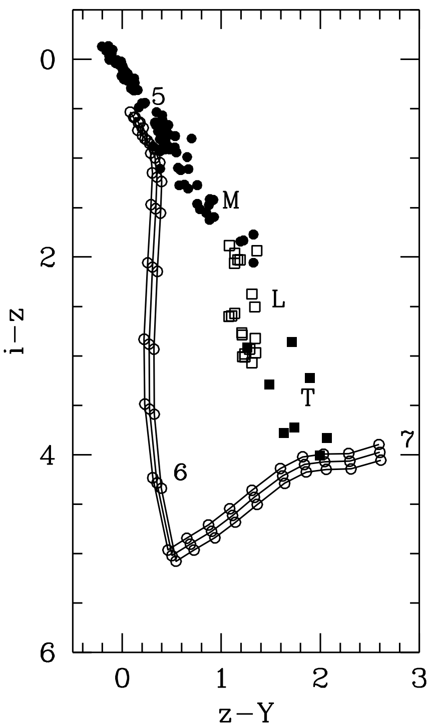

Fig. 2. Two color izY diagram showing colors of main-sequence stars (filled circles), and L and T dwarfs (open and filled squares) (Vega magnitudes). The chains show model quasar colors $5 < z < 7$, $\Delta z = 0.1$ with three different continuum slopes. For $5.4 < z < 6.7$ and $z > 6.8$ these colors are very effective for isolating high z quasars. For $z \sim 6.7$ the quasars will overlap with the very end of the T-dwarf sequence. Courtesy of Steve Warren.

by combining measurements of many supernovae per redshift bin. The surface density of $z \sim 1$ supernovae with $I < 24$ is ~ 4 or 5 per deg^2 per month, ideal for discovery and follow-up with Pan STARRS. With a modest investment of observing time, Pan STARRS can definitively establish the reality of the so-called dark energy.

- **Gamma Ray Burster Afterglows (GRB)** Gamma ray bursters have finally been identified as being at Gigaparsec distances, revealing their tremendous intrinsic luminosities and hinting at their origin in the final phases of collapse of massive stars. The optical afterglows are thought to be synchrotron radiation from highly shocked ejecta and the emission is likely to be highly beamed. GRBs hold scientific potential lies on several levels. Mea-

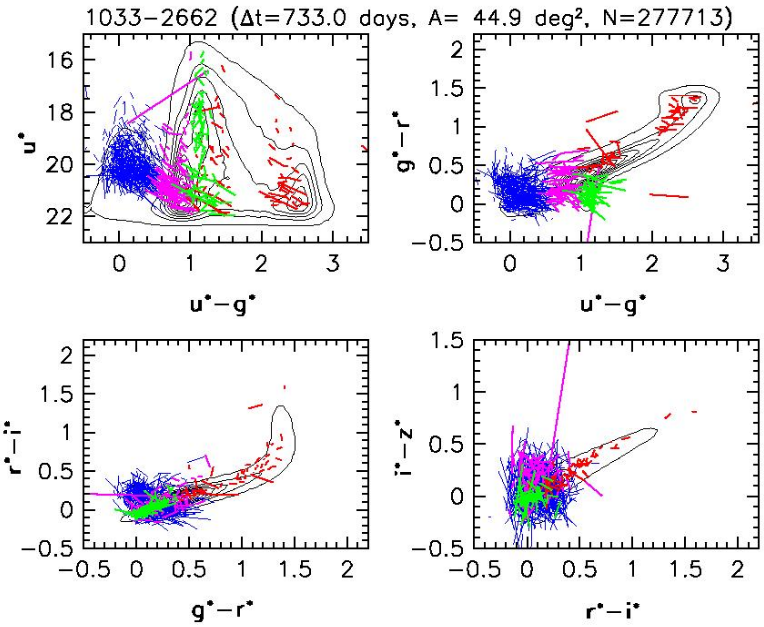

Fig. 3. Types of variability in the color-color plane associated with stellar and extragalactic sources detected in a 75 deg^2 field observed by SDSS 3 yr apart. Colors refer to blue halo turn off stars (pink), RR Lyrae stars (green) and quasars (blue). The reddest objects (in $u - g$ and plotted in red) are probably Mira stars. (Ivezic et al. 2003).

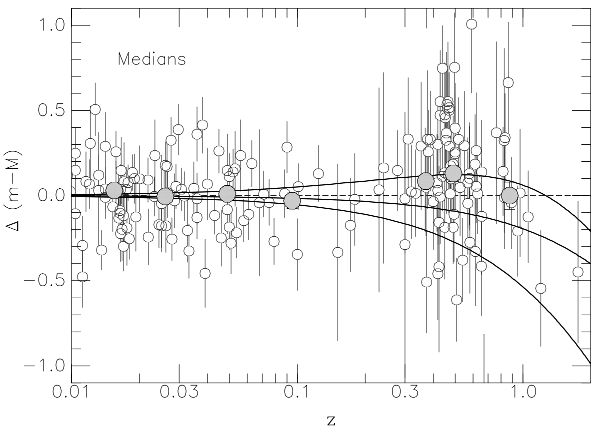

Fig. 4. Hubble diagram computed from supernovae in the redshift range $z \approx 0$ to $z > 1$, relative to an empty universe. The darker symbols show medians of the extant data in redshift bins. From Tonry et al. 2003.

surements of the numbers of detections at gamma ray energies relative to those at optical wavelengths can be used to infer the nature of the beaming of the emitted radiation. Their optical counterparts, if identified early enough, might be used as probes of the intergalactic medium (models and data (Akerlof et al. 1999) show peak brightnesses $V \sim 8$ or 9 declining to $V \sim 20$ in 1 day). And there are hints that the GRB sources might preferentially lie in faint blue galaxies. The whole field is emergent and badly in need of a better sample of optical counterparts, which Pan STARRS will provide in some abundance. The expected rate at $m_R = 24$ is about 10^{-4} deg^{-2}, corresponding roughly to one event every few nights of imaging with Pan STARRS, or of order 100 per year. With a sample of a few $\times 10^2$ optical events, we can begin to correlate these events with the properties of their host galaxies. A small fraction of the events will, serendipitously, be detected early enough to motivate immediate follow-up spectroscopy and spectropolarimetry on another telescope, the latter so far obtained only for one GRB (Barth et al. 2003).

- **Planet Search (EXO)** Planets can be detected photometrically when in transit across the photospheres of their parent stars. The photometric accuracy ($\sim 1\%$) afforded by Pan STARRS restricts the search to planets much larger than 10% of the parent star radius, meaning that Jupiter-sized degenerate bodies cannot be detected around sun-like stars by Pan STARRS. Fortunately, *most* stars are smaller than the sun, while the sizes of planets and brown dwarfs are constant (near 0.1 $R_\odot$) over a wide range of masses. Therefore, Pan STARRS is sensitive to transits of giant planets across sub-solar mass stars. The transit signal of a giant planet crossing a brown dwarf is esentially 100%, since the two are of comparable size. Pan STARRS can detect *Earth* sized planets around brown dwarfs in time-series Z or y band observations, providing differential photometry is possible at the sub-percent level. Staring observations of galactic clusters can net $\sim$300 brown dwarfs simultaneously.

3 Survey Requirements

References

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DESIGN REFERENCE MISSION

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Abstract. In this section we propose an observing strategy that encompasses most of the goals expressed in the Science Appendices. We find that the science goals naturally divide into five modes of operation, or five surveys that fill the available observing time with several science programs feeding from the data within each mode.

1 The Five Pan STARRS Science Modes

The basic observational requirements of the science programs are listed in Table 1. There it can be seen that the total requests for Pan STARRS time amount to about 30 PSY (Pan STARRS Years) when, in the nominal operation of the telescope, only 10 PSY will be available. This is a less severe concern than it first appears, thankfully, because many of the requests for Pan STARRS time can share data if carefully obtained according to the observational requirements. As the most obvious example, GRB science requests 9 PSY but all of these can be combined with other science programs so that no extra data need be taken to satisfy the GRB science goals.

The observational requirements naturally divide the Pan STARRS operations into five basic modes.

- **Solar System Mode** The NEO, MBA, KBO and OSS science programs are united by a common need for maximum detection sensitivity and minimal interest in specific filters. All four programs will be conducted using a broadband filter, about 3500Å wide and roughly spanning the wavelengths of peak quantum efficiency of the detector (the "Solar System" filter). The prime driver is NEO because the Near Earth Objects have the largest rates of motion and place the most stringent requirements on cadence and revisit times to ensure that detections of a given object on multiple nights can be linked with accurate orbital elements. Note that other programs (e.g. AGN and GRB) can use data from the Solar System Mode.
  The NEO program uniquely imposes the need for observations at small solar elongations (the "sweet spots") where the density of the larger potentially hazardous objects is especially high. Such observations would be confined to the early and late hours of the night, and require that the

telescope point at large airmasses (up to $\chi \sim 3.5$) in the east and west. The opposition/ecliptic component of NEO can cover all of the science objectives of MBA and some of KBO and OSS. In fact, because of the lower rates of motion of the more distant bodies studied in KBO and OSS, it is fair to say that the astrometric requirements of the ecliptic parts of these programs will receive more time than they strictly need, all for free, by virtue of piggybacking on NEO.

Caption to Table 1

In the Table, the column heading SS corresponds to the Solar System (broadband) filter, C - cadence, Area - sky area in deg^2 (3π = 30,000 deg^2), PSY - number of requested Pan STARRS Years, M - moon phase (dark or bright), IQ - image quality in arcsec, Phot - required photometric accuracy, Ast - required astrometric accuracy, N - the notes (see below). For each filter and each survey, the first line lists the depth (5σ AB magnitudes) of a single visit using all four Pan STARRS telescopes, and the integration time (in minutes). The second line lists the depth (5σ AB magnitudes) that would be attained by the completion of the survey, and the total integration per footprint.

In the second column we list the proposal acronymns. DT denotes the Deepest Total integration time per footprint by filter. Prop. denotes the proposed integration time per filter for each survey.

Notes to Table 1

a : cadence requirement gives time coverage on scales hours, days and months (see NEO proposal)
b : MBA science can be obtained with NEO observations
c : KBO science can be obtained with OSS observations
d : cadence requirement gives time coverage on scales hours, days, months and years (see OSS proposal)
e : total time consist in NEO over 7000 square degrees and OSS over the remaining of the sky.
f : proposition to use some bright time to follow the sweet spot that does not suffer from moon illumination.
g : cadence requirement of 4 minutes all night long, and use of a different filter on each telescope
h : cadence requirement of 4 minutes all night long
i : total is EXO + VAR
j : EXO part of VAR
k : cadence requirement of 1 visit every 14 days for six months in the first year, then 1 visit per year for 10 years.
l : cadence requirement of 1 visit every 4 days for B and V. r,i,z, and Y have the same cadence requirement as SOL.
m : after first epoch, any data in any band can be used, provided a cadence of 4 days.

		Filters / Depth								C	Area	PSY	M	IQ	Phot.	Ast.	N
		SS	B	V	g	R/r	I/i	Z/z	Y								
Solar System	NEO	24.0/ 0.5 27.5/ 300								y	7000	1.4	D	0.6	0.1	0.2	a
	MBA	24.0/ 0.5 27.5/300								y	7000	1.4	D	0.7	0.1	0.2	b
	KBO	24.0/ 0.5 25.6/ 33								y	3π	0.6	D	0.7	0.1	0.2	c
	OSS	24.0/ 0.5 26.5/ 60								y	3π	1.2	D	0.7	0.1	0.2	d
	D. T.	NEO+OSS								y	3π	2.5	D	0.7	0.1	0.2	e
	Prop.	NEO+OSS								y	3π	2.1+0.4	D+B	0.7	0.1	0.2	f
Star Var.	VAR	24.0/ 1 29.4/22200	24.0/ 3 28.8/7400				24.1/ 5 28.7/4440		20.6/ 5 25.1/4440	y	140	1.7	D+B	-	0.002	-	g
	EXO									y	14	0.2	D+B	0.6	0.02	0.5	h
	D. T.	29.4/22200	28.8/7400				28.7/4440		25.1/4440	y	154	1.9	D+B	0.6	0.002	0.5	i
	Prop.	29.4/22200	28.8/7400				28.7/4440		25.1/4440	y	133	0.8+0.8	D+B	0.7	0.002	0.5	j
3π	SOL					23.9/ 1 25.5/21	23.4/ 1 25.1/21	22.5/ 1 24.1/21	20.7/ 1 22.3/21	y	3π	1.0	D+B	0.7	0.01	0.07	k
	AGN				- 25.5/10	- 25.4/17	- 24.3/5	- 23.2/4	- 22.4/24	n	3π	1.2	D+B	0.7	0.02	0.5	
	FIS				- 25.6/11	- 25.2/11	- 24.1/4	- 23.2/4	- 22.5/30	n	3π	1.2	D+B	0.7	0.02	0.5	
	EGGS		25.0/ 4 27.1/180	24.5/ 2 26.6/90		23.9/ 1 25.5/21	23.4/ 1 25.1/21	22.5/ 1 24.1/21	20.7/ 1 22.3/21	y	3π	2.0	D+B	0.7	0.02	0.5	l
	GRB					23.9/ 1 27.3/2250				y	3π	10.0	D+B	0.7	0.02	0.5	m
	WL				- 26.1/30	- 25.7/30	- 25.6/ 60			n	3π	2.6	D+B	0.7	0.02	0.005 0.5	
	LSB		- 25.8/16	- 25.8/23		25.8/30				n	3π	1.5	D+B	0.6	0.02	0.5	
	YSO									n	3π	-	D+B	0.7	0.02	0.5	n
	D. T.		27.1/180	26.6/90	26.1/30	25.8/30	25.6/ 60	24.1/21	22.5/30	y	3π	8.6	D+B	0.7	0.02	0.5	o
	Prop.				26.1/30	25.8/30	25.6 /60	24.1/21	22.5/30	y	3π	1.3 + 2.5	D+B	0.7	0.02	0.5	p
Medium Deep	LSS				- 27.3/271	- 27.2/458	- 26.1/154	- 25.2/167	- 24.2/625	n	1200	1.3	D+B	0.7	0.02	0.3	
	AGN				- 27.3/271	- 27.2/458	- 26.1/154	- 25.2/167	- 24.2/625	n	1200	1.3	D+B	0.7	0.02	0.3	
	SNE		25.2/ 5 27.3/225	25.0/ 5 27.1/225		24.8/ 5 26.9/225	25.4/ 27 27.5/1200	24.6/ 42 26.7/1875		y	150	0.5	D+B	0.6	0.02	0.5	q
	D. T.		27.3/225	27.1/225	27.3/271	27.2/458	27.5/26.1	25.2/26.7	24.2/625	y	1200	1.8	D+B	0.7	0.02	0.3	r
	Prop.				27.3/271	27.2/458	27.5/26.1	25.2/27.7	24.2/625	y	1200	0.6+0.9	D+B	0.7	0.02	0.3	s
Ultra Deep	SPH				- 29.3/10417	- 29.2/17917	- 28.2/6250	- 27.2/6667	- 26.2/26250	n	28	1.2	D+B	0.7	0.02	0.5	
	AGN				- 29.3/10417	- 29.2/17917	- 28.2/6250	- 27.2/6667	- 26.2/26250	y	28	1.2	D+B	0.7	0.02	0.5	
	SNE		25.2/ 5 27.3/225	25.0/ 5 27.1/225		24.8/ 5 26.9/225	25.4/ 27 27.5/1200	24.6/ 42 26.7/1875		y	150	0.5	D+B	0.6	0.02	0.5	q
	D. T.		27.3/225	27.1/225	29.3/10417	29.2/17917	28.2/6250	27.2/6667	26.2/26250	n	28	1.7	D+B	0.7	0.02	0.5	
	Prop.				29.3/10417	29.2/17917	28.2/6250	27.2/6667	26.2/26250	y	28	0.5+0.7	D+B	0.7	0.02	0.5	t

Table 1. See column description and notes in text

n : no depth requirement, due to variation in extinction. Galactic plane must be covered with red filters.
o : total does not take into account GRB project.
p : EGGS and LSB science still possible using g+r instead of B+V. Cadence requirement of EGGS very constraining.

q : cadence requirement of one observation every 4 days.
r : total assumes SNE + LSS on separate fields.
s : total assumes that LSS will be 4 fields of 300 square degrees, with UDS in these fields, and SNE adding time in i and z over 122 square degrees in the LSS.
t : total assumes that 4 SNE fields will be the UDS. SNE Science does not suffer too much by losing the B and V filter to the g band (Tonry, private communication)

- **3π Mode** The SOL, WL, YSO, VAR, EGGS, AGN, LSB, FIS science programs all require photometrically shallow data over the whole visible sky ($\sim$30,000 deg^2 or about 3π steradians). The main cadence driver is SOL, for which temporal coverage adequate for the determination of parallax and proper motions requires revisits twice per month for 6 months in R and Z, and less frequent coverage in I and Y. The cadence requirement of 4 days for EGGS will be extremely difficult to meet within the 3π survey. WL will, in part, use data from 3π combined without regard to epoch in order to reach all-sky at adequate ($m_R \sim 26$?) depth. AGN science will use data both from the 3π Mode and from the Solar System Mode. The 3π Mode will also generate much useful data for KBO and OSS, both of which require repeated all-sky coverage to about $m_R = 24$.

- **Medium-Deep Mode** Medium depth, medium area field coverage is required by SNE, LSS and can be used by AGN. The driver in terms of area and depth is LSS. The driver is SNE, in terms of cadence requirements, with a nominal revisit time of $\sim$4 days. The objective is to identify a sufficient number of supernovae that can be used to improve the velocity vs. distance relation by averaging. Filter $BVRIZ$ coverage needed for photometric redshift determinations is also useful for the LSS science, and the two programs can be completely intertwined (LSS has no conflicting cadence requirements). The AGN science under the Medium-Deep Mode is to detect evolved stellar populations in galaxies at $z \sim 1.8$, requiring multi-filter images reaching $m_R \sim 26$. Again, this need dovetails perfectly with the SNE science requirements.

- **Ultra-Deep Mode** This mode is required by SPH, AGN, and can be used by SNE. The main drivers are SPH and AGN, which need to reach ultrafaint limiting magnitudes ($m_R \sim 29$) in multiple passbands in order to study galaxies at high z. These high galactic latitude fields would reach the confusion limit for ground-based observations with natural seeing.

- **Stellar Variability** Two projects do not fit easily into the other four modes: VAR for variability studies of stars in the galaxy and EXO to search for planetary transits in heavily sampled, high precision relative photometry of clusters. These define the fifth mode. EXO requests a tiny amount of time (∼0.2 PSY). VAR is more time intensive (∼1.7 PSY).

2 Time Allocations Within the Five Modes

Examination of the time requests given in the science justifications (Appendices) leads to the following division of time among the modes.

Table 2. Summary of Tentative Time Allocations Per Survey

Survey Mode	Dark Time	Bright Time
Solar System	2.1	0.4
3π	1.3	2.5
Medium	0.6	0.9
Ultra	0.5	0.7
Stellar Var	0.8	0.8
TOTALS	5.3	5.3

Within *Solar System*, the MBA observations are conducted totally within time allocated to the NEO survey. The KBO observations likewise can be conducted entirely within the time needed to execute OSS. All the time is dark time. The assumption has been made that all *SolarSystem* observations use the *SolarSystem* filter. Additional time savings in OSS (and KBO) can be obtained by incorporating R band observations to 24th magnitude (i.e. equivalent sensitivity) from the on-going 3π survey, but we need a detailed numerical model of Pan STARRS to see how this should best be done.

The 3π survey places an emphasis on bright time for the red-end filters needed to study, especially, the low mass stars and brown dwarfs.

In *Medium Deep* and *Ultra Deep*, the time is divided between dark (for the short wavelength filters) and bright for observations at I, z and Y.

In *Stellar Variability*, the VAR proposal requests observations in grey time: we have divided the requested 1.7 PSY evenly between bright and dark time on the understanding that much of this could be allocated near half moon (i.e. effectively grey time). The EXO proposal requests an amount of time beneath our current resolution and has been ignored for the present purposes.

The time requested for SNE overlaps with time used for the Medium Deep survey (LSS) and the Ultra Deep survey (driven by SPH and AGN). One major requirement of SNE is that the fields be placed in the sky to provide long arcs of continuous observability (to follow the fading supernovae). This can be done between the 4 fields of Ultra Deep and those of Medium Deep.

Of course, we recognise that the detailed PSY time requests of the different projects will change in the four years between now and first light with Pan STARRS. Our purpose here is less to lock into a fixed set of observing parameters than to establish that plausible observing parameters can be defined given our present understanding of the science and telescope parameters.