Active Objects

1. Discovery and orbital classification of large numbers of active objects to understand and model the onset and termination of activity in the different Solar System small body populations and to explore correlations between physical/orbital characteristics and transient activity.

Quantitative Measure:

2. Discovery/frequency/population estimates of coma and/or dust tail-bearing bodies in the Solar System small body populations including Main-belt comets, NEOs, collisionally impacted asteroids, Centaurs, KBOs, short and long period comets, and interstellar objects to better probe the drivers of such activity and measure the size of these reservoirs.

Quantitative Measure:

3. Detection/frequency/population estimates of anomalous outbursts and rapid brightening/splitting events above the expected brightness evolution of objects in the Solar System small body populations to better probe the drivers of such activity and the size of these reservoirs.

Quantitative Measure:

4. Characterization of the changes in color, morphology, brightness, rotation, shape, and other observable properties of active objects over time (including changes from pre-activity/outburst properties) and at different epochs in the orbits of these bodies to probe surface changes and better explore the various drivers of such activity and their evolution.

Quantitative Measure:

5. Determination of rotational light curves for a large sample of active objects to study physical properties of active objects, including the spin angular momentum distribution, shape distribution, and binary frequency

Quantitative Measure:

6. Detection and characterization of the non-gravitational forces (including jet-driven and collisional accelerations) acting on active bodies to compute better original and future orbits (especially important for identifying dynamically new or long period comets) and estimate rotation poles and seasonal states of active body nuclei.

Quantitative Measure:

NEOs

1. Compilation of an NEO catalog with high completeness and adequate orbit quality.

Quantitative Measures:

Required input: ‘high’ statistics catalogs of synthetic high-fidelity NEOs that are

- Geocentric orbits ($H \geq 30$)
- NEOs ($H \geq 25$)
- Interstellar ($H \geq 22$)
- Earth impactors in the 100 years after LSST begins operations

For some of these, the models described in Grav et al (PASP 2011) may be suitable.

Definition: For the purposes of these metrics, an object is considered ***discovered*** (or ***cataloged***) if it has been detected by LSST with ≥3 tracklets on ≥3 nights that have been correctly linked together.

Note: For the following metrics, a synthetic object catalog that is sufficiently large to ensure good statistics must be used. This can be accomplished in a variety of ways, e.g., using an oversized synthetic population or multiple realistic synthetic populations.

- The fraction of synthetic NEOs with $H<22$ that are cataloged by LSST.
- The fraction of cataloged synthetic NEOs with $H<22$ having a total arc length of ≥180 days.
- The fraction of cataloged synthetic NEOs with $H<22$ having detections on ≥4(tunable?) nights more after ten years
- Detection efficiency on subpopulations
    - Object on geocentric orbits - The fraction of synthetic *geocentric-orbit* objects with $32<H<33$ (i.e. ~1 meter diameter) that are cataloged by LSST.
    - Small NEOs - The fraction of synthetic NEOs with $27<H<28$ (i.e. ~10 meter diameter) cataloged by LSST.
    - Interstellar objects - The fraction of synthetic interstellar objects with $H<22$ discovered by LSST.
    - Large impactors - The fraction of synthetic impactors with $H<22$ cataloged by LSST.
    - Small impactors - The fraction of synthetic impactors with $22 \leq H<25$ cataloged by LSST.

2(a). Color measurements and broad phase coverage of NEOs, including distinguishing NEOs by taxonomy or cometary origin through color measurements and probing the color distribution of ten-meter scale objects.

Quantitative Measure:

The issue with colors is that light curves will obscure colors until there are enough observations in each passband to allow a reasonable mean to be derived. (Unless we have enough data for a LC inversion. See below.) For the moment, the minimum needed to be allow a “reliable” estimate is presumed to be 10 detections having a phase angle range of > 5 deg in each band of interest. There may be a need for avoiding the case where all observations are in a narrow phase angle range, but this is not likely to be an issue for NEOs, and it is not clear what phase angle range should be required for success.

Definition: An object is considered to have a *reliable absolute magnitude and phase function* in a given passband if it is detected in that passband with at least 10 SNR-weighted detections, where the number of SNR-weighted detections is given by

$$N_w = \sum_{i=1}^{n} \left[\min(SNR_i, 20) / 20 \right]$$

Note the *maximum effective SNR =20* in this computation.

- Fraction of cataloged NEOs with H<22 having reliable absolute magnitude and phase function in
    - g and (r or i) and (z or y)
    - Any 4 different filters (from grizy)
    - All 5 from grizy
    - All 6 filters (ugrizy)

2(b). Photometric measurements sufficient for sparse light curve inversion to obtain spin rate, pole orientation and coarse shape

Following the development above, we require an increased number of higher SNR detections to have a good success rate for LC inversion. And we also require a certain level of variation in the observing geometry. We do not require any particular coverage in the various passbands, though that could make a useful additional metric as this is the only way to derive high quality color information.

Definition:

An object is considered to have enough data if it is detected in at least 50 SNR-weighted detections, where the number N_w of SNR-weighted detections is given by

N_w = sum_{i=1}^n [min(SNR_i, 100) / 100]

(Note the *maximum effective SNR =100* in this computation.)

In addition, for the photometric data set to be sufficient it must be well-distributed in geocentric ecliptic longitude λ and phase angle α. Specifically, we require Δλ>90 deg and $\Delta\alpha$>5 deg and the absolute deviation in λ to be ADev(λ) > Δλ/8, where

ADev(λ) = 1/n * sum_{i=1}^n |λ_i - mean(λ)|.

Note that some care must be taken with this equation to properly handle the complexity associated with angle wrapping near λ= 360 deg.

Quantitative Measure:

- Fraction of cataloged NEOs with H<22 having sufficient photometric data sets according to the definition above.
- Median value of N_w for cataloged NEOs with H<22 having sufficient photometric data sets.

3. Timely advance notice of close approaches or potential impacts to facilitate time critical characterization efforts including radar, spectroscopic, and light curve observations.

Quantitative Measure:

- This is primarily a pipeline and latency issue, but also a detection issue. It is not yet clear how best to evaluate this for a given survey instantiation. One could compute, for example, the total count of “warned” close approaches over ten years over some H range. Here “warned” could refer to having a trailed detection (so that it will stand out in the alert stream) at least N days before the approach, or at least M days before it becomes unobservable (by some TBD criteria). Needs discussion…

Farnocchia wrote: It is not really easy to come up with good metrics here.
Here are some ideas, mostly as a starting point to trigger some discussion:

1) Fraction of close approachers in the next 10 years (or more?) that are detected by LSST before the close approach.
And what is the fraction of the objects for which LSST astrometry alone is sufficient to identify the close approach? Or at least identify the low MOID (e.g., < 0.05 au).
This applies to objects that are discovered when far from the Earth for which we expect three separate tracklets within the same lunation, but also to objects discovered when they are close and that are likely trailed.
I am not sure we can incorporate the orbit determination process in the metrics, but I guess we could use some simplified criteria:
- Three tracklets in a lunation
- Two streaks for objects that are discovered when close

2) For radar observations with Goldstone, Shantanu suggests that a lead time of at least three days is needed.
What fraction of close approaches are identified at least three days prior to the close approach? (In theory we need a <~ 1 deg pointing uncertainty three days prior for scheduling, but that relies on follow-up by others so let's leave it alone.)
Arecibo can maybe pull it off with a one-day lead time.
This would only apply to objects of tens of meters, smaller only if the object is on an impact trajectory.

3) For spectra and light curves I am not sure what the needed lead time would be.
Can someone comment on that?
I would think that the requirements are not as tight as for radar, but I may be wrong.

4) In terms of impact and mitigation, we could consider some size categories:
- For an object of a few meters, knowing ~1 day before seems enough. Jenniskens can get on a plane and go there to see the impact!
- For tens of meters, you take the hit but need set up some civil defense actions: one week lead-time?
- For hundreds of meters, we need years of lead-time for deflection missions.

4. Measurement of the orbital, absolute magnitude, and taxonomy distributions within the NEO population, enabling the identification of correlations between taxonomy and orbital properties for all NEOs and the determination of the orbital distribution of ten-meter scale objects.

Quantitative Measure: This is a derived product of #1 and #2. It does not require a new observing requirement.

5. Determination of the long-term impact flux of NEOs as a function of size, for ≥ 140 m bodies in particular.

Quantitative Measure: This is a derived product of #1. It does not require a new observing requirement.

6. Discovery/frequency/population estimates of interstellar objects on unbound orbits passing through the Solar System as a potential probe of planet formation and planetesimal ejection rates in the local solar neighborhood.

Quantitative Measure: See #1.

7. Determination of rotational light curves for a large sample of NEOs to study physical properties of NEOs, including the spin angular momentum distribution, shape distribution, and binary frequency.

Quantitative Measure: See 2(b)

8. Detection and characterization of the non-gravitational forces (including the Yarkovsky effect, solar radiation pressure, outgassing, collisions) acting on NEOs to explore and better understand how NEO orbits evolve over time.

Quantitative Measure: Need very good observational data sets. But, except in rare cases, 10 years is not likely to be enough, even with LSST data quality. Maybe for very small objects (H>22?) with long arcs? [Davide?]

9. Measurement of the absolute magnitude distribution of temporarily-captured objects (NEOs that are temporarily captured by the gravity-well formed by the Earth and Moon) in order to compare to model predictions and to probe the low end of the asteroid size/absolute magnitude distribution.

Quantitative Measure: See #1.

10. Investigation of the possible NEO disruption mechanisms active at small perihelion distances to probe NEO internal structure and test dynamical models.

Quantitative Measure: Fraction of synthetic NEOs with small perihelion distance (q<0.2 au) and small semimajor axis (a<0.7au) catalogued by LSST.

Inner Solar System

1. Discovery and orbital classification of large numbers of asteroids and Mars/Jupiter Trojans to probe their orbital and absolute magnitude distributions and to measure the size frequency distributions of different taxonomic classes.

Quantitative Measure:

Discovery and orbital classification depends on having a number (preferably >4) of observations of the target objects in question. The number of objects to be discovered will be maximized by selecting the correct survey area. In order to get these observations, we require coverage of the full ecliptic plane (all longitudes) preferably with coverage +/- 15 degrees from the ecliptic. We support any efforts to observe the northern ecliptic spur. Unlikely NEOs, some of our objects will have long orbits, so we should not anticipate discovering them in another location on the ecliptic at a different apparition.

We should also be making efforts to consistently update the calculated orbits (or pass this to another group, such as the MPC) as additional observations of known or discovered objects are obtained.

For orbital classification, we require dedicated follow-up to each orbit calculated. For most objects the classification will be easy, but we should also consider the populations with unusual and specific orbits. We should be prepared to identify asteroid family members as a part of this process.

2. Measurement of high quality astrometry for new and previously known asteroids, Mars/Jupiter Trojans, and Jupiter irregular satellites to refine orbits and improve ephemerides for stellar occultation predictions.

Quantitative Measure:

We require (under reasonable conditions and SNR) LSST to deliver astrometry to an accuracy of <10 mas (r<~24.5) for most objects. We expect this high quality astrometry will be consistent over the length of the survey, which will greatly improve the precision of the orbit calculations. One particular use case is the especially high accuracy case of planning and executing stellar occultations by Solar System bodies. For applications to occultations, we prefer measurements to within a few milliarcseconds (1-3?). Extremely accurate ephemerides enables additional science such as the mapping of specific regions of the object (i.e., topography).

3. Detection of impacts of small asteroids onto large ones and detection of asteroid disruption by impact to probe the current collisional environment within the asteroid belt, study dust dynamics, constrain asteroid internal structure, and explore space weathering processes through comparison of surfaces before and after detected impacts.

Quantitative Measure:

Depending on the size and location (distance from Earth), there are two ways to approach this problem. (1) Look for an unexplained change in the apparent brightness of the object and (2) look for a change in the point spread function (PSF).

1. We currently only have a small number of detected asteroid impacts. In the case of (596) Scheila, the magnitude change was about a magnitude (V=13.4) from it's expected brightness (V=14.5). Given the small maximum light curve amplitude of the object (0.10 mag), the large change could be taken as evidence of an interesting event. Unfortunately, there are a number of asteroids with natural lightcurve variations that are larger than the brightness change for Scheila. There are at least two approaches to using an unexplained change in the apparent brightness. First, we can wait until we have a nominal light curve built up for a given object. This is will give us a sense of the natural variation we can expect for an object. Given the sparse nature of the light curves this could be a long wait. We could then have a relatively low value of additional magnitude change that would warrant a notification of change. Second, we can set a value over which the magnitude change is likely not due to the natural variation of the light curve. There are currently only 19 objects in the Lightcurve Database (http://www.minorplanet.info/lcdbquery.html) that have amplitude maxima greater than or equal to 2.0 magnitudes (and only 1 with an amplitude of 3.0 mags). This high limit would likely not catch all of the instances, such as Scheila itself, but could be a valuable backup.
2. The more reliable choice would be to search for changes in the PSF of the objects observation. This was also noticed in the observations that discovered activity on Scheila. If a previously point source object becomes extended, that warrants further investigation.

This process should trigger follow-up observations at other facilities.

4. Determination of colors and compositions for a large sample of asteroids, specifically including Jupiter's irregular satellites, Mars/Jupiter Trojans, Hildas, Cybeles, and Phobos and Deimos to identify correlations with dynamical and taxonomic information with implications for understanding the formation of the inner solar system (e.g., chemical distribution in the primordial disk; collisional family parent bodies and formation events).

Quantitative Measure:

Given the complex nature of the LSST cadence, this is going to be tricky. Asteroid colors are best observed near-simultaneously to mitigate light curve effects. As planned, objects will only have 1-2 colors measured during each visit to the field. We require a minimum of 3 colors to do any compositional analysis, but would any analysis would be greatly improved with 4 (griz). This analysis will require additional software development to use the long baseline of the survey to stitch back together the asteroid colors. This would likely best be done using phase curves in different filters gathered over a period of several years.

We advocate for any opportunity to get 4 near simultaneous color of ecliptic fields. This could be included in the proposed north ecliptic spur survey. This would improve our science (even if the subset of objects observed this way is small) and would enable calibration studies as we work to estimate object colors via the phase curve method.

Given past experience with SDSS asteroid data, we need accuracy for each filter to better than 0.1 magnitudes (r~24.5) to do any population analyses.

5. Investigation of the hydration of C-complex objects and Main Belt asteroids to explore the compositional evolution of the inner solar system and test giant planet migration models.

Quantitative Measure:

See #4 for preliminary information.

For this case, the analyses would depend on measuring a relatively small change in the r and i filters compared to the surrounding continuum defined by g and z. We would need much greater accuracy for these measurements to be conclusive (<0.01-0.02 magnitude errors).

6. Determination of rotational light curves for a large sample of asteroids in different taxonomic classes to study physical properties of asteroids, including the spin angular momentum distribution, shape distribution, and binary frequency.

Quantitative Measure:

We will need a various observations of individual objects over long time scales. Depending on the cadence and orbits, it's possible to get a number of observations at once, but it's unlikely to get the full lightcurve (for an inner Solar System object) within any given observing sequence. The creation of rotational light curves will be a multi-year endeavour. Since not all observations will be in the same filters, we will also need to know the values of the color indices for the objects to best reconstruct the light curves. This process would assume a homogeneous surface, which is a reasonable starting approximation for most objects. Some objects have small light curve amplitudes, so each measurement should have high SNR. In order to reconstruct light curves accurately, we estimate that each frame should have a max error of 0.05 magnitudes (r~24.5), but we prefer lower.

See NEOs section 2(b) for in depth discussion of how this could be connected to light curve inversion and shape models.

7. Improved characterization of newly discovered and previously known asteroid families, clusters, and pairs to study genetic relationships and homogeneity of collisional families at small sizes.

Quantitative Measure:

There are two aspects to this study:

1. The identification of new families and the identification of new members of known families. This investigation requires consistent reexamination of the catalog of known (including LSST discovered) objects. The identification of new family members should be done though a Hierarchical Clustering Model (HCM). The currently known families are very well constrained (e.g., Nesvorny et al. 2015). The HCM could be run for each known family at predefined intervals to gather the newest objects into the family catalog. Alternatively, the orbit of each new object that is not currently associated with a family could be examined once the orbit has been calculated. The basic inputs for these determinations are the astrometry and orbits of the objects. We require high SNR measurements of the asteroid position to make these family association (< 10 mas).
2. The compositional analysis of objects within each family. See #4 and #5. The required accuracy of this investigation depends on the scientific question to be addressed. To find taxonomy, we have much looser constraints (< 0.1 mag errors). For higher level compositional analysis, such as seen in #5, we require much higher precision (0.01-0.02 mag errors).

8. Measurement of asteroid masses and bulk densities from mutual gravitational interactions to probe asteroid internal structures and test planet formation models.

Quantitative Measure:

The observations necessary to observe these gravitational interactions is similar to the high precision astrometry case in #2.

These observations would require extremely high precision astrometry (few milliseconds) for the length of the survey. The time baseline would be very important for this case since the necessary measurement for this investigation is the change to expected positions and orbits. For mutual gravitational interactions between asteroids, these changes are going to be extremely small. This would require the consistent monitoring of the observed asteroid positions relative to their expected positions and of the calculated orbits.

9. Detection and frequency of rotational fission within the non-NEO asteroid populations to probe internal structure and test dynamical models.

Quantitative Measure:

The observations necessary to observe this phenomenon is very similar to the case discussed in #3.

Outer Solar System

1. Discovery and orbital classification of large numbers of outer Solar System objects over a wide range of sizes (H>9) and orbits to characterize the size-frequency-orbit distribution of KBOs and to probe the formation and evolution of the outer solar system (e.g., comet/Centaur pathways, collisional evolution, Neptune migration, etc.).

Quantitative Measure: Early thoughts: a possible target number is an order of magnitude increase over the numbers of presently known objects in each sub-population (e.g., Centaurs, cold classicals, hot classicals, scattering objects, resonant objects?)
[Notes from telecon: don't need a target/requirement, just a metric. What is "discovery": probably mutli-opposition. Discovery rates as a function of H.]

2. Discovery and orbital classification of objects on unusual or extreme orbits, especially inner Oort cloud objects (i.e. Sedna-like objects) with high perihelia (q > 40 au) and objects with very high inclination (i > 40 deg), to place constraints on proposed origin scenarios (e.g., the putative Planet 9; Trujillo & Sheppard 2014; Batygin & Brown 2016; Brown & Batygin 2016; Sheppard & Trujillo 2016; Brown 2017).

Quantitative Measure: Early thoughts: since the properties of these populations are poorly understood, this will require either a synthetic population to test against or specific observational requirements (e.g., 20000 square degrees down to 24.5 with repeat observations that allow objects to be detected at ~100 AU). As per Lynne, could even say "has to distinguish between model X and model Y".

3. Determination of colors for large numbers of objects to identify correlations with dynamical information with implications for understanding the formation of the outer solar system (e.g., chemical distribution in the primordial disk; collisional families).

Quantitative Measure: Early thoughts: Not clear whether sparse multi-color photometry will be sufficient for this. If so, then requiring X% of discoveries have >~Y detections with SNR>Z in >W filters (maybe 75% >30 detections with SNR>20 in at least grz?). If not, then require observations (in different filters) be separated by a short amount of time. How long does it take to get the colors?

4. Determination of rotational light curves for large numbers of objects from different dynamical classes to study physical properties of KBOs, including spin angular momentum distribution and binary frequency.

Quantitative Measure: number of objects with at least 20 observations in a single filter with SNR>20

5. Discovery and orbital classification of large numbers of objects in resonance with the giant planets, especially the libration islands of high-order resonances of Neptune, to constrain models of Neptune migration.

Quantitative Measure: ?

6. Discovery and clear characterization (e.g., PSF shape) of binaries and multiple systems wide enough to be resolved or partially resolved.

Quantitative Measure: number of objects with at least ~5 observations where FWHM was <X arcseconds

7. Measurement of acccurate and precise astrometry for known and new distant Solar System bodies to enable stellar occultation observations.

Quantitative Measure: number of objects with X observations with astrometric uncertainty < Y arcseconds