Large Synoptic Survey Telescope

Gravitationally Lensed Point Sources in the LSST survey

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The LSST survey will contain large numbers of objects currently thought of as "rare," and will image some classes of objects never seen before. Gravitationally lensed quasars are an example of the former, while multiply-imaged supernovae may well fall in to the latter class, and both enable some remarkable science projects. We discuss the prospects for extracting these exciting systems from the survey, and show examples of how analysis being performed on current data is informing our strategy for dealing with the LSST data when it arrives.

Figure 1. The spectacular wide image-separation gravitationally-lensed quasar SDSS J1004+411. Four images of the same luminous background quasar can be seen, centred on the bright cluster elliptical galaxy in the middle of the image.

Strong gravitational lenses (e.g. Figure 1) are powerful tools. The images' separations and time delays provide unique measurements of the total mass of galaxies, and can also be used in probing the cosmological distances, and the scale of the Universe itself. Once calibrated, lenses act as "cosmic telescopes," giving us a new window into the early stages of galaxy formation.

Variable sources are small, and so appear point-like - quasars are the archetypal lens source, and ~100 such systems have been found to date. A great deal of science is possible with such systems, but the statistical power of these studies is limited by the number of lenses in the sample. Here we describe what we expect LSST to be able to contribute to the observational effort. In particular, in such a long-running large synoptic survey, *lensed supernovae alone* will be more numerous than the entire current lens sample: we discuss the challenges of understanding these exciting new objects.

In Table 1 we summarize the properties of two present-day supernovae surveys: they have the depth and cadence to match those of LSST, and so make excellent testing grounds for the high-precision, wider-field science analyses of the future.

	CFHTLS-Deep	SDSS-SN	LSST
Survey area / sq. deg	4	300	20000
Depth per visit (i-band, AB mag)	25.6	21.9	24.5
Filter set	ugriz	ugriz	ugrizY
Typical seeing / arcsec	~0.7	~1.2	~0.7
Pixel scale / arcsec	0.185	0.4	0.2
Cadence / days	6	5	~4-10
Season length / months	5	3	5
Survey length / years	5	3	10

Table 1. Properties of 3 synoptic surveys. See Astier et al (2006), and http://cfht.hawaii.edu/Science/CFHLS/ for more details about the Supernova Legacy Survey at CFHT; the SDSS supernovae survey is described in Frieman et al. (2007) **http://arxiv.org/abs/0708.2749**

QUASARS AND AGN

Ongoing science with lensed quasars includes cosmography via the statistics of these objects, and by the estimation of Hubble's constant, and also the study of the accretion disks in AGN (exploiting its microlensing by stars in the lens galaxy). The anomalous flux ratios of lensed quasars have also provided the first observational hints of the existence of dark, small-scale CDM-like structure in galaxies. Figure 2 shows the expected numbers of lensed quasars – the SDSS surveys referred to here are the main 8000 sq deg spectroscopic and optical ones.

A lensed quasar survey with the SDSS data (Oguri et al. 2006) demonstrates that wide-field optical surveys can be an efficient way to locate many lensed quasars. In the SDSS, lens candidates are selected either to be objects with quasar spectra but extended morphology, or by matching the colors of point sources that are arranged in a lensing configuration. Imaging and spectroscopic follow-up observations are then conducted with many other telescopes to identify genuine lens systems. The survey is still ongoing, but is expected to yield a clean sample of ~40 lensed quasars will be constructed from the SDSS data.

We expect LSST to increase the size of this sample by 2 orders of magnitude – but there will be no survey spectra to repeat the efficient selection of Oguri et al. Instead, we will have to rely on the ugrizY colors, the optical morphology, and the variability of the images (see eg Kochanek et al 2006).

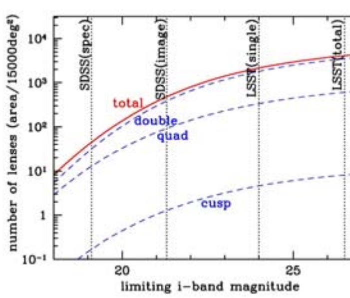


Figure 2 (left, top panel): The expected number of lensed quasars as a function of the limiting magnitude, with various surveys highlighted. The image separation is between 0.5" and 3". Numbers of double, quad, and naked cusp lenses are shown separately. Note that LSST lensed quasars are dominated by double lenses mostly because of smaller magnification bias.

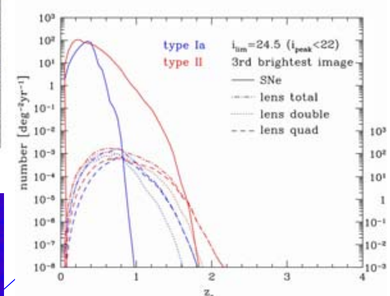
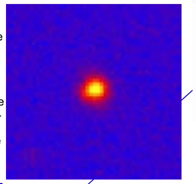


Figure 5: The expected number of lensed supernovae in the LSST survey–the numbers on the right-hand vertical axis are the totals for a 20000 sq deg, 10-year survey. Note that the lensed sample is skewed relative to the unlensed population, favoring higher redshift sources and making, via magnification bias, type IA suernovae more readily observable.



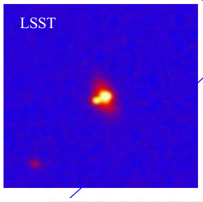


Figure 3: The SDSS image of double lens SDSS J1332+0347 (Morokuma et al. 2007), and the corresponding image that would be taken at LSST (in fact, the "LSST" image was taken with Suprime-cam at Subaru). Two lensed quasar components and a lensing galaxy is seen much more clearly in the LSST image, suggesting that the color-morphology selection of the SDSS lensed quasar survey will be able to be extended to much smaller image separations with LSST.

Figure 4 (right) shows the light curves for all four images of the lensed quasar RXJ1131-1231, measured by Morgan et al. (2006) using a suite of 1-3m class telescopes. It is interesting to compare this observational campaign with that possible with LSST. The data were taken over two 7-month observing seasons at 5-day cadence, with a photometric accuracy of 0.05mag. This enabled the time delays between images (10, 12 and 90 days) to be measured to an uncertainty of just +/- 2 days.

With LSST we can expect the same seasonal coverage, but for an additional 8 years – this brings many more lensed quasars into the sample that are observably varying. The cadence with LSST will be up to 2 times higher – but this is counting all filters. In a single band the cadence will be closer to 10 days.

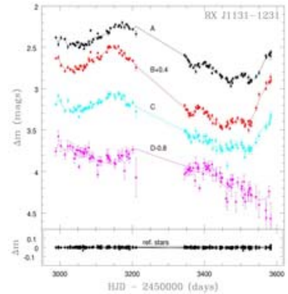


Figure 4: Optical monitoring of the lensed quasar RX J1131-1231. Comparable coverage can be expected with LSST – when combining several filters' light curves.

The combination of the different filters' light curves in measuring time delays will need to be done with care – microlensing is not achromatic, as AGN accretion disks appear to be different sizes in different filters!

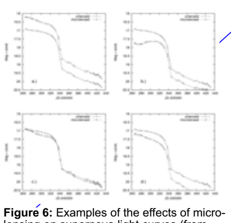


Figure 6: Examples of the effects of micro-lensing on supernova light curves (from Dobler & Keeton 2006). Note the greater variation at early times when the source size is smaller.

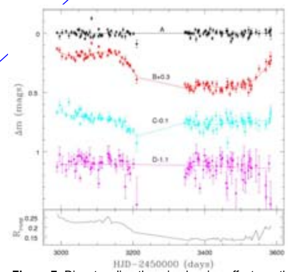


Figure 7: Disentangling the microlensing effects on the four images of RX J1131-12 (Morgan et al 2006). The differences between each light curve and that of image A are clearly seen to contain a separable microlensing signal.

Experience with current supernova surveys is essential for catching the few hundred lensed objects we expect to see with LSST. The bulk of the lensing cross-section lies in massive elliptical galaxies; monitoring these (selected by color and morphology) in the LSST database will be our basic strategy. However, lensed supernovae, like any other supernovae, will be flagged by the SN pipeline: we just have to ensure that the difference imaging works well in the presence of bright elliptical galaxies.

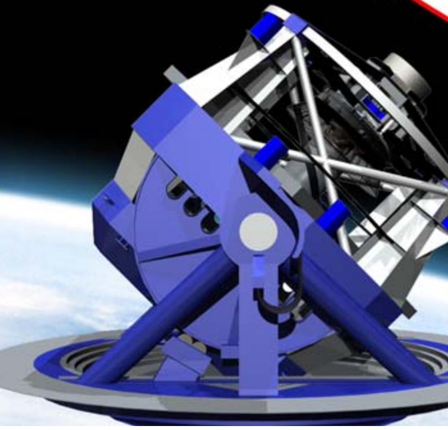
Even in early-type galaxies, the frequency of SNe is expected to approach that of the lensed supernovae rate: modeling of the image positions and timings (see movie frames below!) will be important in setting up an alert system. The second and third images of a quad system are the bright ones; the first image is usually dimmer, and the fourth image the faintest. For doubles, the second image is the less bright, more central counter-image. The appearance of the third image of a quad system, in its expected location, should certainly be a trigger – but there may only be a few days delay between the two!

The SN is likely to be microlensed by stars in the lens galaxy. When monitoring lensed quasars (Figure 7), Morgan et al have shown that such signals can be modeled concurrently with the underlying source variation, provided the cadence and photometric accuracy is high enough. The variations occur as the physical size of the SN increases during the explosion – we can hope to measure this expansion from the lensing data.

SUPERNOVAE

No lensed supernova has yet been seen – but we expect the LSST survey to contain several hundred with well-measured light curves.

If the source is a type IA standard candle, then the mass sheet degeneracy is broken and one of the main sources of systematic error in the estimation of Hubble's constant is removed (eg Oguri et al 2003). The time delay measurement is likely to be limited by microlensing (Dobler & Keeton 2006, see figures above) – this effect provides a unique window into the physics of supernova explosions, and their influence on galaxy formation in the high redshift Universe.



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