

build a very large-aperture space telescope than to provide the same-sized aperture on the ground. From the present vantage point, GSMT is arguably on the traditional side of that comparison that space telescopes are more expensive, but if NGST succeeds at the 8-m size for its proposed budget, apertures much larger than GSMT may be approaching this crossover point. Experience with GSMT and NGST technologies will help formulate the answer as to whether even larger ground-based telescopes, for example, the proposed 100-m OWL telescope, are more cost-effective than space telescopes.

3.8 Ancillary Benefits

A 30-m with its superb angular resolution and sensitivity may be the preferred way to follow up extremely faint sources associated with X-ray, Gamma-ray, and micro-Jy radio sources, particularly if more than merely a redshift is desired. Should NGST not be achieved, GSMT's existence becomes an absolute necessity for progress in the fields described above.

4. Priority 2, Major Initiative: A Large-Aperture Synoptic Survey Telescope (LSST)

4.1 Mission Description

We advocate the construction of a Large-Aperture Synoptic Survey Telescope with the ability to map the entire accessible sky to 24th magnitude (in one optical band) over the course of 3 nights. (This is about a magnitude deeper than the Sun would appear at the distance of the Magellanic Clouds, or the Milky Way galaxy seen at a redshift $z = 1$.) The science objectives, which range from Solar System science to cosmology, can be addressed *simultaneously* with the same set of images. For the first time, astronomers and the general public would have access to a "motion picture" of the night sky.

The requirements for the proposed system follow from the expression for signal-to-noise ratio in a sky-dominated exposure, yielding a figure of merit that scales as $A\Omega/\sigma^2$, where A is the system's effective aperture, Ω is the field of view of the focal plane, and σ is the seeing. To map out the 20,000 square degrees of accessible sky down to 24th magnitude every few nights will require the equivalent of a 3° field of view on a 6.5-m aperture telescope.

The detectors of choice for the temporal monitoring task would be thinned CCDs; the requisite extrapolation from existing systems appears to be a small technological risk. A comparably wide field IR-capability is considerably more challenging, but could evolve as a second phase of the telescope's operation. Instrumentation for LSST is an ideal way to involve university/independent observatories with this basically public facility.

[FIGURE 8 LOCATION]

4.2 Science with LSST: The Wide Area Variability Experiment

The unprecedented capabilities of LSST open up the possibility of a new kind of science program, a *wide area variability experiment*, WAVE, where one or a few simple survey modes can simultaneously address a suite of front-line science questions.

- Near Earth Objects (NEOs) The orbits of many asteroids intersect the orbit of the Earth. These so-called Near Earth Objects (NEOs) present a threat to life on our planet, with effects ranging from the local damage inflicted by smaller members of the NEO population, for example, the blast wave destruction of 10^3 km² of Siberian forest at Tunguska in 1908, to global disruption of the biosphere, as occurred with the Cretaceous/Tertiary event, by the impact of a 10 km body.

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Extrapolations from recent surveys suggest that there are of order 10^3 NEOs larger than 1 km in diameter and as many as 10^5 to 10^6 measured down to 100 meters. The vast majority of these objects have yet to be discovered, but a statistical analysis indicates a 1% probability of impact by a 300-m body in the next century. Such an object would deliver 1000 MT of energy and (given an average surface density of people on Earth of 10 per km^2) result in 10^5 fatalities. The damage caused by impact near a city, or into a coastal ocean, would be orders of magnitude higher. Of course, the distribution is extremely non-Gaussian: the majority of impacts would have a far smaller effect with a small fraction having a catastrophic result. Regardless, impact clearly constitutes an extreme example of the influence of the astronomical environment on the Earth.

The reality of the impact threat has been recognized by scientists only in the last 20 years. In the last 5 years, thanks to several reported near-miss encounters with small objects, it has become a subject of intense interest to the general public and has even been discussed in the U.S. Congress. Although it can be argued that there are other threats to life on Earth whose risks exceed that of asteroid/comet impact, the public attitude is clearly that any significant risk that is *avoidable* deserves attention. The contribution of astronomers to this task is to find these objects with sufficient warning (decades) that counter-measures might be taken.

[FIGURE 9 LOCATION]

A survey for NEOs demands an exacting observational strategy. To locate NEOs down to the 300-m size range demands a surveying down to magnitude 24, a capability 5 magnitudes beyond that of existing survey telescopes but well matched to LSST. NEOs spend only a small fraction of each orbit in the vicinity of Earth. Repeated observations over a period of 10 years are required to explore the full volume of space occupied by these objects. During this time, LSST would discover NEOs at a rate of order 100 per night, and obtain astrometric information on a much larger (and growing) number of NEOs previously discovered by this facility. Precision astrometry is needed to determine the orbital parameters of the NEOs and so to assign a hazard assessment to each object. Astrometry at weekly intervals would insure against loss of these fast-moving objects in the months and years after discovery.

- Kuiper Belt Objects (KBOs). Kuiper Belt Objects are the most primitive bodies in the Solar System. Because their orbital dynamics and compositions carry the imprint of the formation of the Solar System, they are arguably the most important missing piece in our attempts to understand this fundamental process. For example, already we have evidence for injection of comets from the Kuiper belt, and for the ejection of matter to the Oort Cloud and interstellar medium. It is further important to model the collisions between KBOs which generate a dust ring around the Sun—this is a local analog of dust rings recently discovered around nearby main-sequence stars.

KBOs are among the most challenging objects in the Solar System to discover and study. A deep census with LSST is needed to establish the orbital and gross physical properties of 10^4 KBOs—such a large sample is needed to model the complex dynamical structure of the Kuiper belt. For example, many KBOs occupy mean-motion resonances with Neptune (as does Pluto). Dynamical models of the early Solar System suggest that the relative populations of different resonances can be used to measure the rate and total distance of Neptune's migration, which is itself a measure of the mass ejected outwards by Neptune

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towards the Oort Cloud. However, with samples as small as the 60 KBOs with known orbits, a majority of the resonances appear empty and population ratios cannot be accurately determined.

The science requirement to accumulate 10^4 KBOs provides an independent driver to the design and operation of LSST. The luminosity function of the KBOs shows that about 10^4 such objects brighter than red magnitude 24 are to be found in the whole sky. The survey must therefore cover the whole sky in a band centered on the ecliptic and extending $\pm 30^\circ$ from it to red magnitude 24. The coverage must be repeated at intervals from weeks to months near discovery, rising to yearly once the orbits have been approximately determined. We estimate that all 10^4 KBOs could be discovered within 1 year on LSST. Subsequent astrometric observations for orbit refinement would take up a quickly diminishing fraction of the time in subsequent years. The KBO survey would operate concurrently with the NEO survey described above.

- Searching for other planetary systems. Two techniques will be used: Occultations and microlensing. A typical gas giant planet (a degenerate hydrogen body with a radius fixed near 10^8 meters) has a cross-section about 1% of a solar mass main-sequence star (radius about 10^9 meters). In the occultation technique, stars will be monitored with sub-percent photometric precision to search for the periodic dimming as a companion planet crosses the face of the star (for those orbits aligned with the line of sight). Assuming random distribution of orbital planes produces an occultation probability per planet-bearing star of order 10^{-3} . If, as Doppler velocity measurements suggest, 1 star in 20 possesses a gas giant planet then the probability of detecting a planet by occultation is of order 5×10^{-5} per star. However, accurate photometry of $\sim 10^8$ stars is completely feasible with LSST, so repeat measurements at intervals short compared to the orbital period should detect some 5000 gas-giant planets. Such a large sample has great value, for example, the incidence of planets could be determined as a function of stellar spectral type (mass).

By exploiting the remarkable phenomenon of gravitational microlensing of distant stars, intensive monitoring can be used to search for planets with masses as small as the Earth's. The essential requirement is that the apparent planet-star separation be comparable to the Einstein radius. This requirement is not especially stringent. For example, if our own Solar System were to be observed in this way (from a location 10 kpc distant against a lens 5 kpc away) we would find a signal from Jupiter in almost 20% of solar microlensing events.

The planet-search program imposes two requirements on LSST. First, LSST must generate photometry accurate to a few tenths of a percent. This is a modest requirement even for stars at 20th magnitude given the quality of modern CCDs and the large aperture of the LSST. Second, each star must be re-observed at intervals comparable to or less than the crossing time (about 1 day for both the occultation and microlensing methods). It is probable that planet-search observations could be conducted using the same survey data obtained for the NEO and KBO surveys.

- Observational cosmology with supernovae. Type Ia supernovae have been demonstrated to be excellent distance indicators. A program of repeated scans of the sky will detect about 100,000 supernovae per year. The nearby ones can be used to trace out departures from smooth Hubble flow caused by the non-uniform distribution of dark matter. More distant supernovae found by LSST (followed up with deeper imaging on other large ground- and space-based telescopes) will complement studies of the small-scale anisotropy of the microwave background that also measure cosmological parameters such

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as matter and dark energy density. Distant supernovae are also a powerful probe of the history of star formation over cosmic time.

- Studies of astrophysical variability. The resulting archive of stellar variability will provide a fundamental resource for studies of stellar astrophysics. The discovery of large numbers of eclipsing binaries with a broad range in masses and chemical compositions would provide fundamental data such as masses and radii for comparison with models. Temporal data for extragalactic objects, particularly AGNs and lensed quasars, are powerful probes of the nature of the extreme environments surrounding massive black holes.
- Detection of rare transient objects. By mapping the entire accessible sky to 24th magnitude, we will open up a vast new “discovery space.” Optical counterparts of Gamma Ray Bursts are one example of unanticipated phenomena that reside in the time domain—there are surely others. It has been suggested that some of these events become very bright (~8th magnitude) for short periods of time. If so, and if they can be detected rapidly enough, these optical transients will be powerful probes of the intergalactic medium, surpassing in distance and detail what can be done with quasars.
- White dwarfs in the Galactic halo. Imaging of large areas at high Galactic latitude repeated over a period of years using optical (VRI) colors will uncover, through their proper motions, a complete sample of halo white dwarfs. If, as the MACHO microlensing experiment suggests, a major component of the Galactic halo is stellar mass objects of ~0.5 solar masses, the best candidate is a population of very old, very cool, low-luminosity white dwarfs. A deep survey at VRI colors would have the best chance of detecting both those with hydrogen-rich (and infrared H₂ dipole opacity dominated) and helium-rich atmospheres.
- A deep digital map of the sky. By co-adding repeated scans of the sky, LSST will produce digital composite images of unprecedented depth. For example, in the course of a year, images of combined depth 2.5 magnitudes fainter than a single image will be produced, corresponding to a limiting magnitude of 26.5. With these will be generated well populated catalogs of rare and unusual objects for spectroscopic study with the generation of 8-m telescopes. The spatially coherent distortions of the images of faint, distant galaxies will be used to map out the structure of foreground mass concentrations, using the signature of weak gravitational lensing. Such wide-area, deep images can also be used to search for faint objects such as ultra-low-surface-brightness galaxies.
- A deep infrared map of the sky. With very modest integration times, a sufficiently large infrared detector array (beyond current feasibility) could be used to generate a map of the sky that is 100 times (5 magnitudes) deeper than the 2MASS data set. This would fill the gap between the existing data and the IR limits of the current generation of large aperture telescopes. For example, an all-sky survey to J, H, and K ~ 20 would reach deep enough to detect what may be the majority population of field brown dwarfs in the immediate solar neighborhood. Recent simulations suggest that many local constituents are expected to have temperatures much below 1,000 K; as mentioned, these could be too faint for the ongoing 2MASS and Sloan surveys, and too rare per unit surface area for infrared surveys covering limited regions of the sky.

4.3 Theory Challenge for LSST

A Theory Challenge for LSST is to understand the origin, relationships, and fate of small bodies in the Solar System. as described in the report of the Theory, Computation, and Data Exploration Panel.

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Historically, the Solar System has provided us with nature's most revealing dynamics laboratory. Newton formulated his laws of gravitation largely to explain new measurements of the motions of the moon and planets. More recently, the importance of dynamical chaos was first discovered in the Solar System by astronomers studying the orbits of asteroids. The new LSST observations of vast numbers of Solar System and other objects promise new material from which exciting developments in theory are to be expected.

4.4 Data Flow and Information Distribution

The LSST + WAVE is an ambitious program: it will be a path-breaking undertaking, providing unequalled opportunities for developing real-time data mining tools and techniques, and for testing the scaling properties of database structures and algorithms.

Because this endeavor is so challenging, it is important to recognize that it builds upon current successes in high-data-rate projects in optical astronomy and derives great benefit from advances in the computing world. Increasing availability of cost-effective computing and mass storage hardware is surpassing the data rates produced even by ambitious astronomical instruments. For example, the factor of 100 increase in data rate from present microlensing surveys (initiated in the late 1980's), which produce 5-10 GBytes of raw image data per night, to the ~1 TByte per night rate expected for the WAVE project (starting in the mid 2000's) will be more than compensated by advances in computing and mass storage.

Hardware is only part of the solution to the data processing problem, of course. The software must (1) process the data stream in near real time, (2) detect and classify variable and moving objects, and (3) place the results in a readily accessible data repository. Considerable experience has already been gained in these tasks from microlensing surveys, and the Sloan Digital Sky Survey (SDSS) and 2MASS Survey are adding a wealth of new software that can be applied, both conceptually and specifically, to future projects.

An example step in a data reduction pipeline is the detection of variable objects. Experience from the microlensing surveys suggests that perhaps one object in 1000 will exhibit statistically significant variability. With 10 billion objects in the sky within the grasp of LSST, a catalog of ~10 million variable astronomical sources will be generated. It seems clear that this new view will have a profound impact on astronomy and astrophysics, in areas ranging from the study of quasars and AGN, to gamma ray bursters, supernovae, variable stars, planets, comets, and asteroids. General-purpose image analysis tools keyed toward variability are already in the final stages of development. These routines unify the recent progress developed in supernova and microlensing search projects. By automatically scaling and transforming two images so that an accurate subtraction can be performed, the separation of variable objects from more plentiful non-variables becomes straightforward. To date the *classification* of detected variability (into Solar System objects, supernovae, microlensing, etc.) has been done by humans. Several groups are presently devising a machine-assisted way to carry this out—we note that this is a prime example of a cross-disciplinary activity, mutually beneficial to both the computer science and astrophysics communities, that NSF should be eager to support.

The challenge of implementing an effective database and user interface for large volumes of astronomical data is a common thread in the astrophysics of the coming decade, which should be spearheaded by the National Virtual Observatory initiative. The Virtual Observatory will add great leverage to the WAVE data set, which will contribute the temporal dimension to the aggregate data set, while taking full advantage of unified data structures and user interface developments. The WAVE database will by itself likely be the largest non-proprietary data set in the world—it will be an ideal resource for testing the scaling and efficiency of data mining tools and techniques.

A considerable effort will be required to construct a system producing roughly a Terabyte of raw data per night, with rapid data reduction of images, classification of variability,

characterization of sources, and rapid distribution of the data. We emphasize that it is crucial to consider LSST + WAVE as precisely that: a complex system for which the telescope and instrument are only the front end.

4.5 Multiplicative Advantages and Discovery Space Potential

One of the most attractive aspects of LSST is that it can pursue simultaneously many of the science goals described above. The time domain is (with a few notable exceptions) largely unexplored in astronomy. WAVE will provide unprecedented access to the theater of the sky, and will pay tremendous dividends to a wide variety of scientific objectives beyond these. The benefit of a continuing, deep, O/IR sky survey to future space missions and ground-based radio astronomy should be considerable. The technology for the construction of the optics and instruments is well in hand, and the project could play a leadership role in applying state-of-the-art information technology, in order to provide rapid distribution of useful data to both the scientific and lay communities.

4.6 Technology and Cost Issues

Telescope. Based on the existing successful projects of this size, and allowing for a more complex optical system, we estimate the construction cost of a 6.5-m telescope with a 3 degree field at \$60M.

Instrumentation. The state-of-the-art in currently deployed mosaic CCD arrays is 10K x 12K pixels. Cameras of 18K x 18K are presently in development, and there is no fundamental impediment to achieving the roughly 30K x 30K array that would be required to cover the 3 x 3 degree field of LSST. Paving the field of LSST at 0.3 arcsec/pixel with existing 2K x 4K CCDs would require 162 devices, at a detector cost of roughly \$6M. Optics, mounting, cryogenics, electronics and system integration would add ~\$10M, for a total instrument cost of \$16M.

A second-generation instrument using IR detectors is an obvious migration path for the system, but would greatly benefit from further developments in the footprint of IR arrays.

Data Processing and Distribution Pipeline. Current high end workstations with 250 Gbytes of disk, a few GBytes of memory, and multiple processors cost approximately \$20K. The real-time analysis pipeline will require roughly 10 TBytes of disk space, and the equivalent of perhaps 50 current high end workstations. At *current* prices this analysis system would cost approximately \$1M, and the cost for this performance will fall steadily with time.

The estimation of software costs are less certain. Starting with experience gained with SDSS and 2MASS, and the current state-of-the art in variability analysis, implementing the WAVE analysis pipeline should require approximately 30 FTE-years of programming effort, at a cost of \$3 Million. Developing the requisite data structures, and a user interface will likely require a comparable effort, for a total software capitalization cost of \$6M. Maintenance and upgrades should be budgeted at an annual cost of 10% of the initial software investment, or 6 FTEs (\$3M for 5 years of operation).

The data repository costs will depend on the degree of synergy with the National Virtual Observatory, and amount of user support that is provided. We estimate (based on experience gleaned from the microlensing projects) that the volume of reduced data will be roughly ten times smaller than the raw image data. This implies a time series data base that would grow at a rate of roughly 20 Terabytes per year. Ideally this would be stored on magnetic disks, at a cost of roughly \$5M per year if implemented at current prices.

