Title

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ABSTRACT

The Supernova / Acceleration Probe (SNAP) is a proposed space-borne observatory that will survey the sky with a wide-field optical/NIR imager. The images produced by SNAP will have an unprecedented combination of depth, solid-angle, angular resolution, and temporal sampling. Two 7.5 square-degree fields will be observed every four days over 16 months to a magnitude depth of $AB = 27.7$ in each of nine filters. Co-adding images over all epochs will give an $AB = 30.3$ per filter. A 300 square-degree field will be surveyed with no repeat visits to $AB = 28$ per filter. The nine filters span 3500–17000Å. Although the survey strategy is tailored for supernova and weak gravitational lensing observations, the resulting data will support a broad range of auxiliary science programs.

Keywords: Astronomical imaging, wide-field surveys

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1. INTRODUCTION

The unexpected discovery that the Universe's expansion is accelerating, as measured by supernova experiments[1,2] and independently confirmed by cosmic-microwave-background experiments,[3,4] implies that some heretofore unknown form of energy is driving the Universe's dynamics. The existence of this so-called "dark energy" lies beyond the current framework of elementary particles and thus has profound implications for fundamental physics. The challenge now is to measure the physical properties of this dark energy and the most mature approach to do this is with a next generation high-redshift supernova search and discovery experiment.

The Supernova / Acceleration Probe (SNAP) is proposed in this spirit. As a dedicated space-borne observatory, SNAP will provide supernova data, in the form of light curves and spectra, of unprecedented quality. The photometric instrumentation suite is tailored specifically for the needs of the supernova program; a wide-field imager in the optical and NIR provides a high discovery rate of $z < 1.7$ Type Ia supernovae (SNe Ia) and allows for multiplexed followup, ~ 50 supernovae within a single exposure. The supernova fields will be revisited every four days for 16 months, providing light curves for at least several months in the rest frame of each supernova.

Also part of the SNAP primary mission is a weak gravitational lensing survey. Lensing provides an independent and complementary measurement of the cosmological parameters through the mapping galaxy shape distortions induced by mass inhomogeneities in the universe. The strengths that make SNAP excellent for supernova observations apply to lensing as well; a wide-field imager in space with stable and narrow point-spread-functions can provide large survey areas, accurate shape measurements, and high galaxy surface densities. The SNAP supernova fields will serve as a deep lensing field while a second larger-solid-angle field specifically tailored for lensing will be observed to a shallower depth.

In this paper, we quantify the expected depth, solid-angle, and time resolution of the SNAP SNe and weak lensing surveys. In §2 we describe the SNAP mission: the important properties of the telescope and camera as relevant to imaging and the observing cadence and exposure times of the primary SNAP science missions. The depths of the surveys naturally produced by these programs are given in §3. A sampling of possible auxiliary science that can be done with these data is given in §4 and a brief summary is given in §5.

2. DESCRIPTION OF MISSION

In this section, we briefly describe the SNAP telescope and its instrumentation suite as relevant to its imaging capabilities. The observing program for the primary supernova and lensing missions are also detailed. It is based on these properties that we calculate the depth of the resulting surveys. The numbers provided here and throughout this paper are SNAP specifications.

2.1. Telescope and Instrumentation

The important properties of the SNAP telescope[5] are given in Table 1. SNAP has a 2-m primary aperture and 16% obscuration from the secondary and metering structure. The spot size of the telescope optics is less than 0.05" RMS over the focal plane. The optical telescope assembly is composed of four silver-coated reflectors each with 98% throughput.

Table 1. Parameters of the SNAP telescope that are relevant to determining imaging capabilities.

Telescope	Primary Aperture (m)	Secondary Aperture (m)	Primary Obscuration	Spot Size (arcsec)	Throughput (@ 1μm)	Jitter (arcsec)
SNAP	2.0	0.4	0.16	0.05	0.92	0.02

The SNAP camera[6] has $f/\# = 10.83$ and throughput of 70%. The camera tiles 0.7 square degrees, split in area between LBNL CCD's[7] and 1.7μm cutoff HgCdTe devices.[8] The detector properties are given in Table 2. The detector pixel sizes give undersampled images; spatial resolution will be recovered by taking several dithered

Table 2. Parameters of the SNAP detectors that are relevant to determining imaging capabilities.

Detector	Pitch (μm)	Read Noise (e^-/pixel)	Dark Current (e^-/sec/pixel)	Diffusion (μm)	Peak QE
LBNL CCD	10.5	4	0.002	4	0.92
HgCdTe	18	5	0.02	5	0.6

images for each pointing.[9] When imaging, the detector noise is sub-dominant to the zodiacal background and thus has a negligible effect on the error budget.

The zodiacal background will be the dominant source of background light given SNAP's orbit and shielding of Earth-shine. This relatively faint wavelength-dependent background toward the ecliptic poles is shown in Figure 1.[10] The cosmic-ray flux of 2×10^{-4}/sec/pix will require multiple measures to avoid significant contamination of the images as will be discussed in §3.

The PSF is diffraction dominated but we include effects such as CCD diffusion, telescope jitter, and the telescope spot blur. At bluer wavelengths, the contribution of these secondary blurs do have a noticeable effect on the PSF. For our photometric measurements, it is the PSF size that determines the noise contribution of sky background.

The SNAP filter set consists of nine Johnson B filters logarithmically distributed in wavelength with effective wavelengths at 4400×1.15^nÅ for $n \in \{0, 1, ..., 8\}$. We have a fixed filter design; the six optical filters are uniformly distributed over the CCD's while the three NIR filters occupy equal areas of the HgCdTe devices. In total, each optical filter covers 0.056 square degrees while each NIR filter covers 0.112 square degrees to constitute the entire 0.7 square degree field.

The detectors are arrayed in an annulus; the SNAP three-mirror-anastigmatic design has a flat pickoff mirror near the Cassegrain focus that totally vignettes the central region of the field. The symmetry of the filter layout allows a fixed side of SNAP to always face the sun while maintaining a consistent footprint of the fields over an entire year. Figure 2 shows the layout of the imager in the focal plane, and the relative sizes and positions of the filters.

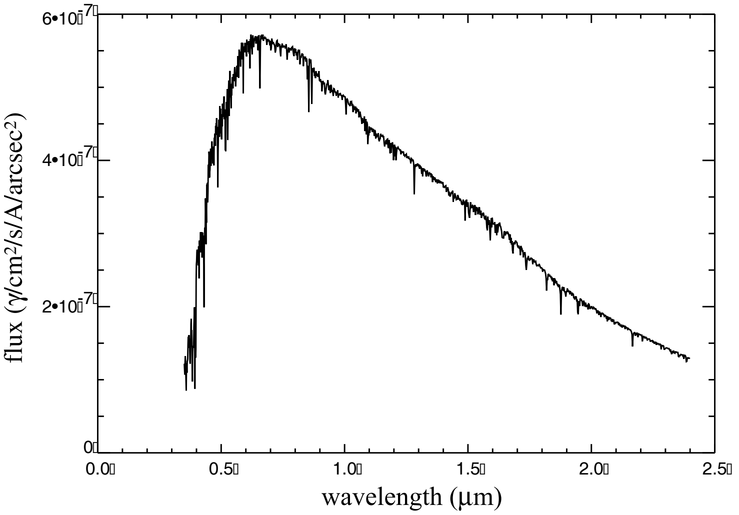

Figure 1. The zodiacal background will be the dominant source of background light for SNAP. Shown is the zodiacal photon flux toward the north ecliptic pole, the planned location for one of the SNAP supernova surveys.

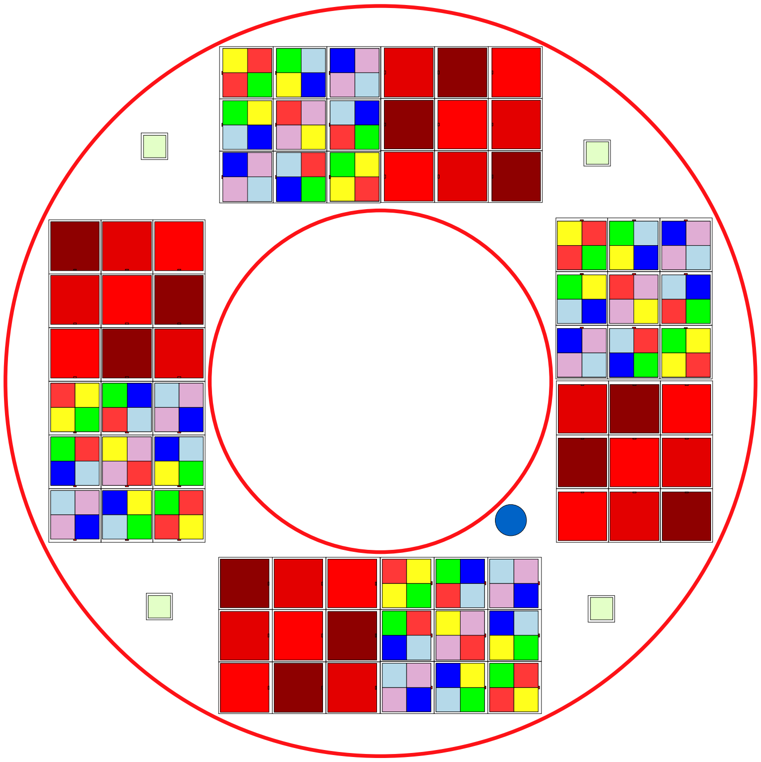

Figure 2. The layout for the SNAP imager. Detectors tile 0.7 square degrees of the focal plane. In the fixed filter scheme, six optical filters are mated to CCD's and three NIR filters are mated to HgCdTe detectors. An individual optical-filter tile subtends $2.9' \times 2.9'$ and an individual NIR-filter tile subtends $5.8' \times 5.8'$. The four star guiders are shown as isolated squares located between the science detectors. The circle at the inner part of the annulus is the light-access port for the spectrograph.

2.2. Observing Strategy

The two primary SNAP science programs have individually designed observing schedules which are described here and summarized in Table 3.

2.2.1. Supernova Program

The supernova survey is comprised of two halves, both in time and in position. The initial survey will cover 7.5 square degrees over sixteen months pointing toward a field near the north ecliptic pole. After an intervening weak-lensing survey, a similar field toward the south ecliptic pole will be observed.

Observations in multiple bands allow SN-frame B and V coverage for SNe from $0 < z < 1.7$. As shown in Figure 2, the filters are arrayed in a checker-board pattern. In the absence of a filter wheel, multi-band exposures of a point of sky will be achieved by shift-and-stare observations where the pointings are shifted by the 2.9' width of the optical filters. Each pointing will consist of four 300-second exposures; the multiple exposures are for cosmic-ray rejection and dithering of our undersampled pixels. Within a scan, 116 pointings are required to cover the 7.5 square degrees of the north field. Thus, in one scan any one optical/NIR filter will cover 6.5 square degrees while 5.44 square degrees will have observations in all nine filters. The wider NIR filters will experience twice the exposure time of the optical filters. A scan will be repeated every four days for 16 months for a total 120 scans.

Forty percent of the SNAP mission will be spent doing targeted spectroscopy of supernovae. Imaging occurs simultaneously during these spectroscopic observations. The resulting images will cover random positions and orientations within the SNAP field and can be used to increase the depth of the survey. However, these extra images are not considered in the calculations given in this paper.

2.2.2. Weak Lensing Program

The weak lensing program calls for a five-month wide-field survey to obtain as much solid-angle as possible within the constraints of telemetry. Repeat observations are unnecessary. Multi-filter data, particularly in the NIR, is desired for accurate photometric-redshift determination. The specific geometry of this field is yet to be determined. The important observing parameters of the two programs are summarized in Table 3.

Table 3. The SNAP Surveys.

Program	Solid Angle per filter (sq. deg.)	Exposure per scan (s)	Cadence (days)	Visits
SN	6.5×2	Optical: 4×300 NIR: 8×300	4	120
Lensing	300	Optical: 4×500 NIR: 8×500	...	1

3. DEPTH OF OBSERVATIONS

The telescope and camera properties of SNAP have been modeled and incorporated into an advanced exposure-time calculator(ETC).[9] Besides having all the bells and whistles of a standard ETC, our ETC includes unique handling of the pixel response function, undersampling, dithering, and probabilistic cosmic-ray rejection. As mentioned in §2 SNAP will rely on dithering to recover spatial resolution from its undersampled pixels.

The high cosmic-ray flux produces a non-trivial reduction of effective exposure times; pixels from a single exposure that are contaminated by a cosmic ray are assumed to be recognized through median filtering and dropped in the dithered reconstruction. Short individual exposure times limit the contamination: 300 second exposures give a 68% probability that there will be no cosmic-ray contamination on any of the four dithers that make up a pointing at a given position.

The magnitude depths for individual scans and co-added images of the SNAP supernova fields are calculated for each filter. The limiting magnitude for any given point is probabilistic, due to the random occurrence of cosmic rays. Table 4 shows the 50%-ile limiting AB magnitude for a $S/N = 5$ point source for each filter in the surveys.

The SNAP observing strategy provides remarkably even depth over the range of filters. For a given filter, individual scans of the supernova and lensing surveys are only ~ 0.75 magnitudes shallower than the Hubble Deep Fields (HDFs) whereas the SN fields co-added over time are ~ 1.5 magnitudes deeper than the HDFs.[11] SNAP has the additional advantage of having nine filters observing to this depth, compared to the four filters of the HDFs, and 9000 times the area. Furthermore, most of the surveyed area will be observed in all filters; when these data are combined, the limiting magnitude increases by 0.6 magnitudes.

SNAP fields will contain many faint diffuse galaxies whose detection is important for the weak-lensing surveys. The limiting magnitudes for Gaussian-aperture photometry of an exponential-disk galaxy with FWHM=0.12" are shown in Table 5.

4. SCIENCE

In this section we give a brief discussion of possible science that can be obtained from the SNAP surveys. This list is by no means complete in its breadth nor depth. The expected results from the primary SNAP science missions are discussed in a companion paper.[12]

Table 4. The SNAP 50%-ile AB magnitude survey depth for a point source $S/N = 5$. Random cosmic-ray hits make the S/N for a given position probabilistic.

Filter	λ_{eff}(Å)	SN (AB mag)		Lensing (AB mag)
		Scan	Co-added Scans	
1	4400	27.9	30.6	28.3
2	5060	27.8	30.5	28.2
3	5819	27.8	30.4	28.1
4	6692	27.7	30.4	28.1
5	7696	27.7	30.3	28.0
6	8850	27.5	30.2	27.9
7	10178	27.5	30.2	27.8
8	11704	27.4	30.1	27.8
9	13460	27.4	30.0	27.7

Table 5. The SNAP AB magnitude survey depth for an exponential-disk galaxy with FWHM=0.12" with $S/N = 10$.

Filter	λ_{eff}(Å)	SN (AB mag)		Lensing (AB mag)
		Scan	Co-added Scans	
1	4400	26.4	29.1	26.8
2	5060	26.3	29.0	26.7
3	5819	26.3	29.0	26.6
4	6692	26.2	28.9	26.6
5	7696	26.3	28.9	26.6
6	8850	26.2	28.8	26.5
7	10178	26.3	28.9	26.6
8	11704	26.2	28.9	26.6
9	13460	26.2	28.9	26.5

The Sloan Digital Sky Survey(SDSS)[13] and HDFs[11,14] have demonstrated the vast range of science that can be obtained from wide and deep multi-band surveys. SNAP will produce surveys that dwarf the 0.0016 square degrees size of the HDFs and go even deeper with time-sampling for its supernova fields. The SNAP lensing field is about the same size as the Sloan Southern Survey and CFHT Legacy Survey fields but several magnitudes deeper. This combination of depth, temporal coverage, filter coverage over a broad wavelength range, diffraction-limited seeing, and wide field make SNAP imaging surveys uniquely powerful in the study of a wide range of objects:

- Galaxies — SNAP fields will contain $> 5 \times 10^7$ galaxies within detection threshold. Statistical studies are possible with such a large sample, e.g. the determination of the galaxy luminosity function and color distributions as a function of redshift. The depth allows for inclusion of low-surface-brightness and very high-redshift galaxies. Accurate photometric redshifts and information on galaxy evolution will be available from the multi-band and in particular the NIR photometry. High resolution images will provide a view of the internal structure of galaxies and their kinematic interaction with each other.
- Galaxy clusters — Wide-field imaging and photometric redshifts allow easy identification of galaxy clusters. The epoch of galaxy-cluster formation is tightly linked with the mass density of the Universe, Ω_M, providing an independent cosmological measurement complementary to SNAP's primary missions.
- Quasars — The NIR photometry extends the redshift range for quasar discovery ($6.3 < z < 12$) using colors and dropout surveys. Discoveries will also move much fainter into the quasar luminosity function.

The highest redshift quasars can be used to map the reionization history of the Universe through the Gunn-Peterson effect. SNAP's ability to identify diffuse objects associated with quasars can have profound effects on the study of galaxy formation.

- Transients/Variables — The discovery and observation of SNe Ia are the primary goals of SNAP, but transient "backgrounds" are interesting in their own right: quasars, active-galactic-nuclei, gamma-ray-burst optical counterparts, supernovae of other types, variable stars, and eclipsing binaries. Of particular interest to cosmology is time-delay studies with the expected large number of strongly lensed variables. Gravitational microlensing surveys of stars and quasars are also possible.
- Stars — Faint limiting magnitudes and excellent star-galaxy separation will yield faint dwarf and halo stars. Proper motion can be detected with high-resolution and a long time baseline. The geometry and substructure of the halo and disk in the direction of the SNAP fields can be mapped.
- Solar-system objects — The peculiar motion in the time-series data will facilitate the identification of local objects such as asteroids and Kuiper-belt objects.

The output from the SDSS has demonstrated how the natural byproducts of a wide-field survey can produce scientific yield well beyond the scope of its primary purpose. Individual objects found on SDSS images are routinely observed spectroscopically at the largest telescopes in the world, fulfilling the historical trend of small-aperture telescope imaging feeding targets for large-aperture telescope spectroscopy. The SNAP surveys should be no different and will play an important role for NGST and the next generation of ground-based overwhelmingly large telescopes.

5. SUMMARY

The primary science missions of SNAP will provide survey fields in nine filters spanning 3500–17000Å.

- A 300 square-degree field to AB mag $\sim$ 28 at $S/N = 5$ in each filter.
- Two 7.5 square-degree fields observed every four days 120 times. Each observation reaches AB mag $\sim$ 27.7 at $S/N = 5$ in each filter. A fraction of these fields, 2×5.44 square degrees, will be observed in all 9 filters.
- The co-added sum of all visits from the preceding survey: two 7.5 square-degree fields to AB mag $\sim$ 30.3 at $S/N = 5$ in each filter.

We have restricted our discussion to surveys produced by the principal science missions of SNAP[*]. A guest observing program is envisioned to fill the remaining satellite lifetime; given a compelling science case new SNAP imaging surveys are possible.

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[*] The numbers presented here describe the SNAP reference mission. They are subject to change as trade studies are performed to optimize the design of the experiment. The reader is advised to exercise caution in extrapolating these results to other possible survey missions; the SNAP primary-mission fields have continuous visibility, allow for stable satellite orientation, ensure shielding of background light, and point to regions of relatively low zodiacal background.

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