The Synoptic All-Sky Infrared (SASIR) Survey: *A Transformative Science Initiative by Mexico and the University of California*

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Abstract

We are proposing an ambitious project – to survey, synoptically, the entire night's sky at infrared wavelengths to unprecedented depths using a dedicated wide-field 6.5-meter telescope in San Pedro Martir (SPM), Mexico. The concept is part of a new initiative for a ground-based telescope in partnership with Mexico and the University of California. What the Sloan Digital Sky Survey (SDSS) and Large Synoptic Survey Telescope (LSST) are to the Digitized Sky Survey (DSS), this project will be to the seminal 2 micron All-Sky Survey (2MASS). The science drivers for the synoptic all-sky infrared (SASIR; pronounced "sassier") survey are numerous, from discovery of the precious and rare high-redshift QSOs in the static sky to uncovering and studying numerous obscured and red transients. We expect to have major impact on almost all topics of astronomy, from the study of low-mass stars and exoplanets to fundamental cosmology and the detection and study of transient events. This short *whitepaper* describes the concept, drivers and preliminary survey plans. Upon completion of the IR survey, we will further exploit the capabilities of this 6.5m telescope and the tremendous site of SPM, with one possibility being a fiber-fed spectroscopic survey.

Infrared Astrophysical Survey Science

As a modest-cost survey by current standards, 2MASS has had a transformative impact on astrophysics, revolutionizing the study of low-mass stars, Galactic structure, and the low redshift universe. There are over 2500 papers written citing 2MASS data despite the rather humbling fact that each place in the sky was imaged for only 7.8 seconds. The key to the success was the novel 3-color imaging at infrared wavelengths, whereas all other sky surveys had focused on optical wavebands. The benefits of not only repeating that survey but increasing the depth and time coverage would itself be transformative. To do so would require nearly continuous access to a large aperture telescope. Is a new large telescope required given the current landscape of facilities? Indeed, the planet already supports a glut of 8m class telescopes: eight in each hemisphere, nearly all of which do or will carry a full suite of traditional instrumentation. The majority of these facilities have a relatively narrow field-of-view ($< 20'$) and are optimal for faint or high-dispersion spectroscopy. In 3m-class telescopes, there is a growing emphasis on large-scale programs and/or large field-of-view imagers, e.g. 2DF, SDSS, UKIDSS, VISTA, MOSA, ODI. Finally, innovation in 1m-class telescopes is in fully automated, rapid-response systems, primarily for IR and optical imaging.

In the near future, there are three main potential areas for significant advances: (i) ambitious time-domain experiments on the ground (eg., Pan-STARRS, LSST) and in space (e.g. Kepler, JDEM), (ii) the next generation of large (> 20m) telescopes, (iii) space-based astrometry (e.g., GAIA, next generation SIM). From the ground, the wide-field surveys are focused entirely on optimal imaging (4000 – 10000 Å). The JDEM missions may push to $\lambda = 1.6\ \mu$, but will not provide multi-time epoch coverage over the entire sky. The large-aperture telescopes will rely on adaptive optics imaging in the near-IR to attain diffraction-limited science over a small field of view. The astrometric missions will provide geometric distances to every detected optical source ($R < 20$ mag) within several kpc but will not have adequate temporal or spectral coverage to fully characterize the demographics of the sources detected. It is within this context that we seek a project that will both compete with and enhance current and future facilities.

Science Drivers

As discussed in the telescope design section, the final survey depth after 4 years would be about 1000 times more sensitive than 2MASS, nominally increasing the survey volume to more than 30,000 times that of 2MASS. This would have an enormous impact in the study of rare, faint, and red objects. In the following we highlight just a few science applications of telescope+instrument design in two categories: time domain and static sky science.

Time Domain

Discovering the Traveling Solar Neighbors. Extrapolating out the number density of stars less than 5 pc from the Sun to 25 pc, suggests we are missing more than 50% of stars from our census. Those objects are almost certainly M-dwarfs and brown dwarfs, i.e., faint and red stars. Some those stars are almost certainly observed in 2MASS but not recognized as local neighborhood systems (e.g. Ruiz, Leggett, Allard). A synoptic survey would reveal such systems (and those fainter) both through parallax and proper motion measurements. We expect only a few such new systems per thousand square degrees. Completing the 25 pc census would be a significant achievement, not only in informing studies of the initial mass function of stars but by providing fertile grounds to study low-mass (and their binary companions) stars with the largest telescopes. Indeed, such stars in the local neighborhood would become ideal systems to observe Earth-mass exoplanets.

Galactic variables: Keys to the Distance Ladder. Though RR Lyrae and Cepheid variables make up key components of the cosmic distance ladder, the uncertain distances coupled with uncertain dust and metallicity corrections translate directly into uncertainties in cosmological parameters. The European astrometric mission, Gaia (to be launched in 2011), will revolutionize Galactic distant measurements by providing geometric parallax measurements for RR Lyrae and Cepheids to tens of kpc. The SASIR survey would allow for a precise calibration of the period–luminosity relations of these two variable classes at infrared wavelengths, largely skirting the problems with dust. Moreover, Sollima et al. (2006) have suggested both that infrared portion of RR Lyrae spectra are relatively immune to metallicity effects and that the intrinsic shape of the RR Lyrae light curves at infrared wavelengths make them more conducive to use as standarizable candles. Over several years of the survey, such variables (then with known distances and with known periods) would be observed several times at random phases allowing for the construction of an unprecedented calibration of the period–luminosity relations. This, in turn, would allow AO-enabled 30 meter telescopes to measure precise distances well-beyond the local group and finally fix the rungs of the cosmic distance ladder out to ~ 25 Mpc.

Infrared Supernovae: The Low-redshift Lever Arm for Cosmology. With the first uniformly observed IR survey, we (Wood-Vasey et al. 2008) have recently shown that **Type Ia supernovae** are better standard candles in the IR than at optical wavebands; since Ia SNe are the *de facto* events from which dark energy and quintessence parameters are to be honed with JDEM, this revelation foists the importance of a large IR survey for Ia supernovae to the fore. At B-band maximum, $H(AB) = -16.61$ mag suggesting that SASIR should be able to discover IR Ia supernovae to $z = 0.16$. If a few months per year were dedicated to a rolling search, SASIR would provide good phase coverage before and after maximum light for SNe with $z < 0.1$ for thousands of SNe. Aside from improving IR templates, given that that the supernova found would be relatively devoid of the dust systematics that plague Ia optical discovery, such data would form the basis low redshift sample for Ia cosmology in the infrared. That same search would uncover and observe dozens of **Type II-P supernovae**, a class of supernovae to which distances can be determined irrespective of the cosmic distance ladder. Recently, it has been shown that the optical imaging and spectroscopy of such events might rival Type Ia supernovae as standardizable events from which Hubble diagrams can be reliably drawn (Nugent et al. 2006). Given the relative immunity to dust, lower flux dilution, and the location of the spectral peaks blueward of the IR, Type II-N supernovae should be even better standard events in the IR (see Schmidt, Kirshner & Eastman 2002).

Counterparts for high energy and multi-messenger astrophysics. High energy astrophysics is one of the last frontiers. While gamma-ray astronomy is undergoing rapid development, driven by new space telescopes like *GLAST* and ground based facilities, neutrino and gravitational wave astronomy are just now in their infancy. Beginning in 2008, *GLAST* will perform daily monitoring of the entire sky at GeV energies, with the expectation of providing several thousands of gamma-ray sources positioned with arc-minute accuracy. We already know the high energy sky is dominated by powerful variable sources, whose nature can only be deciphered by finding the proper counterparts and understanding their multi-wavelength and temporal behavior. *GLAST* will be complemented by ground based TeV gamma-ray Čerenkov telescopes, limited by their narrow fields of view, and water Čerenkov observatories, limited by their angular resolution; all these high energy γ-ray facilities will facilitate the opening of the new messenger windows: neutrino and gravitational wave astronomy. Much of the science extracted from these observations will require the identification of electromagnetic counterparts, hindered by their inabilities to locate events to better accuracy than about one degree on the sky. Even those with *GLAST* counterparts will require deep and continuous coverage of the improved arc-minute locations to pinpoint and follow up their counterparts. All these facilities will demand rapid access to multi- wavelength wide-field deep imaging, with increasing emphasis on the time domain. Therefore, there will be a burning need to have rapid access to wide-field deep imaging to find out highly variable signatures. The SASIR system should be ideal for such discoveries and could lead to a new cottage industry in tandem with these new vistas of the universe.

Static Sky

As noted in the introduction, there are several ongoing and nearly commissioned IR surveys with ground-based 4m telescopes. In terms of science with the 'static sky', these projects will compete directly with the SASIR survey. SASIR, however, has two principal advantages over the planned and existing surveys. The first is full coverage of the northern sky. The only other IR survey in the northern sky is the UKIDSS project which will image only 1/5 of the full area and only to a relatively shallow depth. The 4 year SASIR project would represent a qualitative leap over UKIDSS. The second is unparalleled depth over 20,000 square degrees. Although the VISTA project will cover a similar area, it will do so only in a limited filter set (JK) and to a much shallower depth than SASIR. As such, our project will be the premier program for identifying the faintest, rarest, reddest

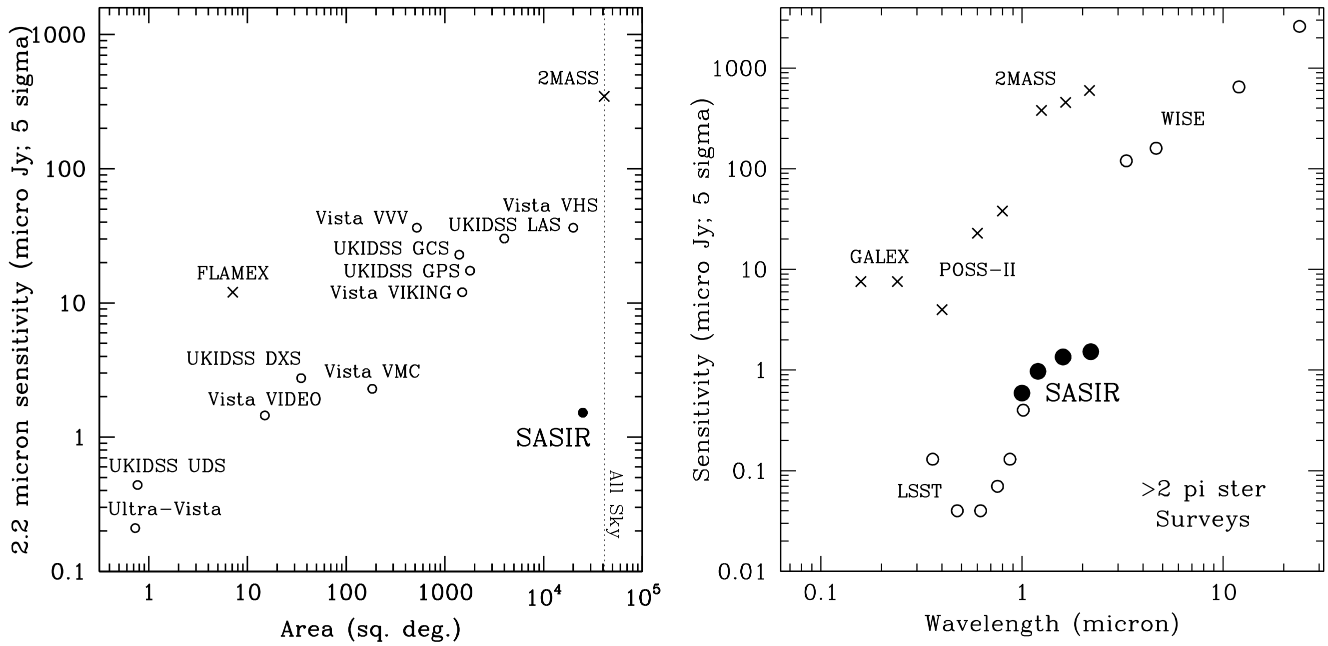

Figure 1 *Comparison of the SASIR survey with other significant IR surveys already completed (× symbol) or planned (o symbol). Left: The point source K-band sensitivity versus sky coverage. Right: The point source sensitivity versus wavelength for wide-area surveys. Survey data compiled by D. Stern (JPL).*

objects in the universe. Here are a few examples of the forefront science that would be enabled:
High Redshift Quasars: A premier extragalactic science case for SASIR is in the discovery of high-z quasars. These objects track the growth of supermassive black holes in the early universe, mark the sites of intense star-formation, and contribute to the reionization of the universe. At present, there are only a handful of quasars known at $z \sim 6$ and none at $z > 6.5$. The observational challenges to discover these objects are threefold: (i) the intergalactic medium absorbs most if not all photons in optical pass-bands making IR imaging essential, (ii) the objects are very rare so that large areas of the sky must be surveyed, and (iii) at $z > 6$, these intrinsically bright objects become very faint.

One can estimate the number of such sources that SASIR will detect by extrapolating the quasar-luminosity function at $z < 6$ to higher redshifts. Figure 2 shows the predictions for several high z intervals corresponding to quasar detections in the Y, J and H filters. It is evident that the detection of hundreds of $z > 7$ quasars demands deep magnitude limits a and large survey area. The figure also indicates the survey parameters for the UKIDSS/LAS, VISTA/Viking, and SASIR/4yr projects. The first two programs will likely discover several tens quasars at $z \sim 6$ to 7 and none at higher redshift. SASIR, in contrast, will provide thousands of quasars at $z \sim 6$ and hundreds of candidates at $z \sim 10$. The challenge will quickly become obtaining spectroscopic confirmation, a task well-suited for the JWST and TMT projects.
Other areas: There are also a number of less exotic, yet extremely valuable science projects that SASIR will enable. For example, in the first few passes of the sky, the survey will have sufficient depth to provide near-IR magnitudes for every spectroscopic target in the SDSS dataset. The K-band imaging alone will yield a stellar mass census of the $z \leq 0.1$ universe to unprecedented levels. These IR data best trace the large-scale structures that galaxies populate and will reveal the nature of dust-obscured star-formation in the local universe. At high redshift, IR imaging is the most

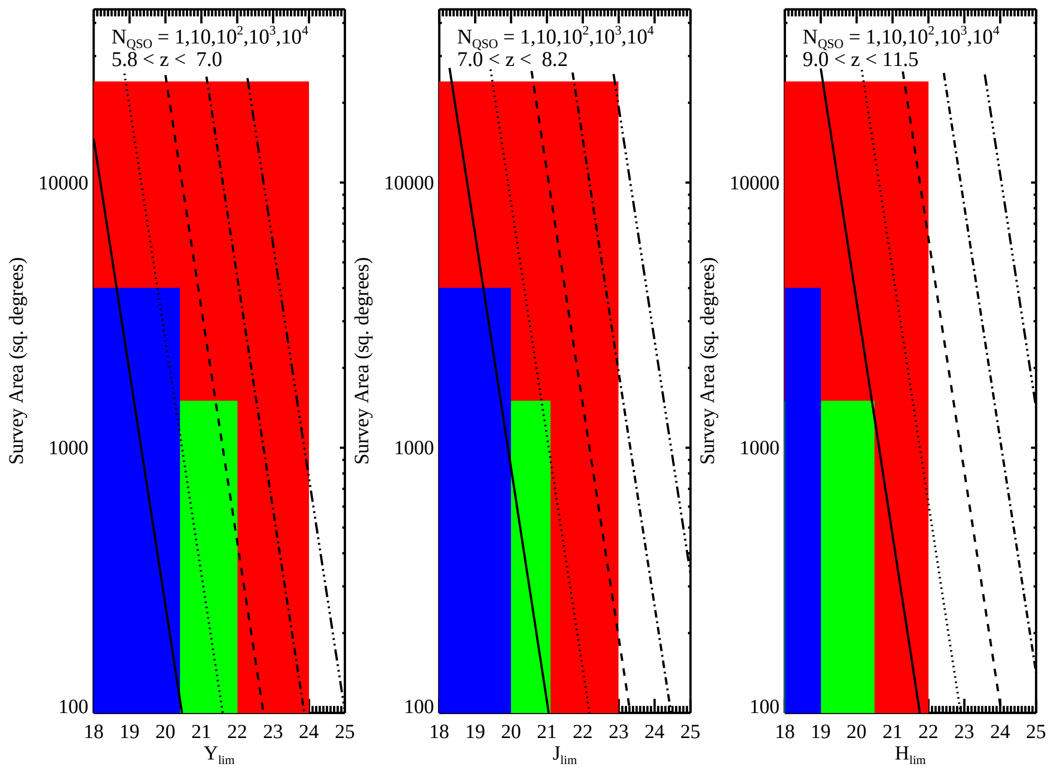

Figure 2 *Predicted quasar candidates as a function of redshift and survey design (SASIR=red, VISTA=green, UKIDSS=blue). Note that VISTA and UKIDSS are unlikely to recover any $z > 8$ candidates while SASIR may reveal ~ 100. Similarly, at $z \sim 6$, UKIDSS and VISTA will identify several tens of the brighter candidates whereas SASIR will resolve the full luminosity function.*

efficient means of minimizing the 'catastrophic' photometric redshift errors that plague weak lensing and other $z \sim 1$ large-scale surveys. In addition, SASIR would uncover highly obscured AGN, reveal very reddened star-forming galaxies, and discover the faintest 'red-and-dead' galaxies of the local universe. Within the Milky Way, the SASIR survey will provide an unprecedented survey of low-mass stars in the northern sky.

Telescope Concept

The telescope will be a modified version of the Magellan 6.5 telescopes at Las Campanas Observatory. Given the expense for science-grade IR detectors, our design is driven by a desire to cover a large field of view with the fewest pixels while still adequately sampling the good seeing at San Pedro Martir. This is driving us to a split-beam design for the camera, like 2MASS, to simultaneously image in 4 filters. The optical design of SASIR is bound by a few main constraints: the aperture and curvature of the primary mirror (F/1.25), a field of view (FoV) greater than 3/4 of a degree, a plate scale of ≈0.25" per 20 μ pixel (F/2.5 net system), an after-construction-under-operation image quality that does not deteriorate by more than a few percent the median NIR seeing, a high efficiency design (greater than 30%) at least within the 0.8-2.4 μ range, and a system with low thermal emission from its optical components that also permits the proper buffering of scattered thermal emission.

A wide set of two and tree mirror telescopes are under consideration in order to find an optimal

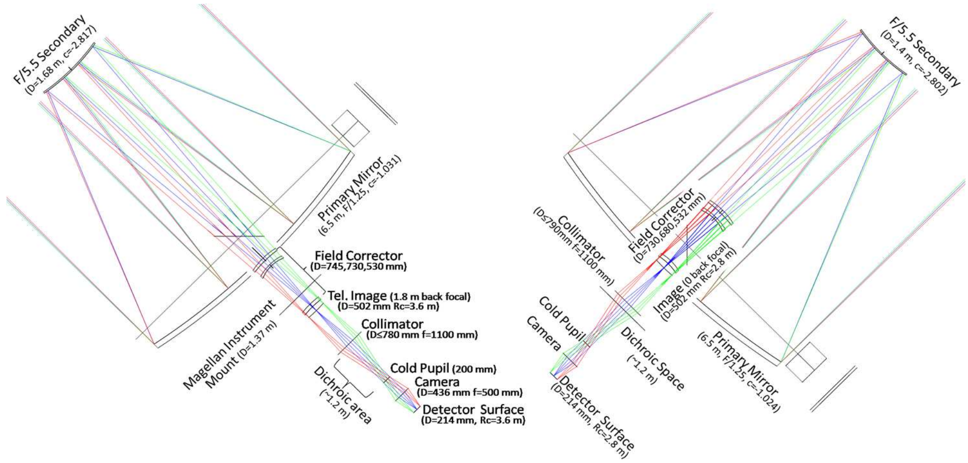

Figure 3 *SASIR Telescope reference concept (Magellan nominal back focus at right, null back focal at left). A single arm is shown with schematic paraxial camera and collimator (folding dichroics not drawn). The telescope and corrector deliver and effective F/5.5 focal, the whole system is F/2.54. Relevant characteristics of the main components are shown.*

solution that permits up to four cameras, each with 0.8 FoV, with NIR refractive optics under about 500 mm in diameter. At this moment, the reference concept consists of a F/5.5 Ritchey-Chretien design with a 3-lens field corrector (all spherical, Silica-like glass). In order to allow for a cold pupil as well as the placement of dichroics, the telescope is coupled to a focal reducer, with a collimated beam of 200 mm and a camera with focal length of 500 mm.

Figure 3 shows two reference concepts, for simplicity with perfect (paraxial) collimator and camera. The first one maintains the Magellan back focal, and in the second the telescope focus is at the primary vertex, to explore the range in which the diameter of the secondary and the height of the pupil can be controlled. Both telescope designs deliver an image quality close to the diffraction limit across the whole FoV, between 0.03" and 0.1" FWHM. These idealized (pre-construction) telescope performances tell us that essentially the whole optical error budget can be left for the collimator and camera designs as well as for the construction and operation of the entire system.

In summary, we do not expect significant problems in the design of the telescope; the main remaining issue is to guarantee enough room in the collimated beam(s) for dichroics and a cold pupil, and the size and design of the collimator(s) and camera(s).

The nominal detectors are 2048 x 2048 arrays with 18 or 20 micron pixels, now commercially available for about \$350,000 (though volume discounts could make the nominal cost about \$200,000). This translates to 0.23 – 0.25 arcsec/pixel and would require 80 – 90 arrays in the focal plane (assuming a 75% filling factor). In less than a few second integration, the sky in all bands would swamp the readnoise of even moderate-quality detectors; this will allow for flexible and dynamic imaging as the science requires. In survey mode, we expect $\sim$20 second dithered exposures. For a total on-source dwell of 80 seconds (2 visits per night consisting of 2 integrations each) and nominal slew time to next field of 6 seconds, we expect to cover about 140 sq. deg per 9-hour night, implying that the entire visible sky from a single site could be imaged every 3 months. Table 1 shows the expected point source and extended source sensitivities. A nearby star with $Ks = 20$ mag would be localized to 5 milliarcsec rms, suggesting better than 10 σ parallax measurements to objects within 20 pc.

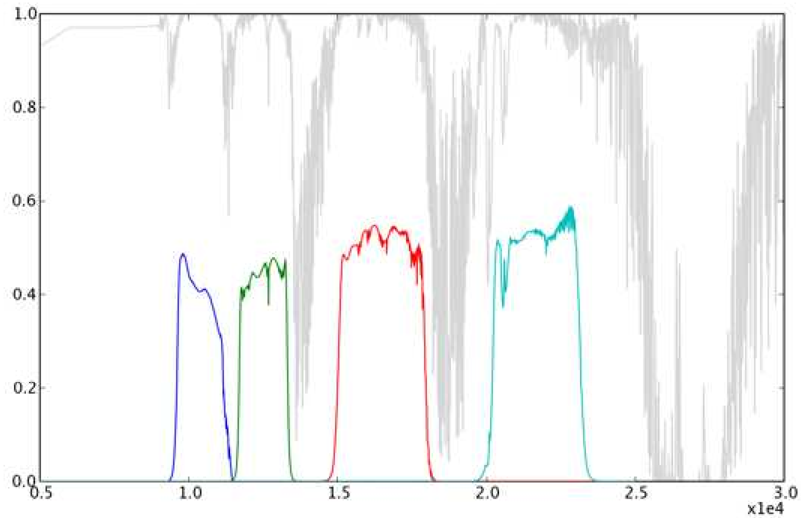

Figure 4 *The absolute SASIR Survey filter response curves (from left to right: Y, J, H, Ks) along with the atmospheric transmission window. The response curves include optics, mirror reflections, quantum efficiency of the IR arrays, and atmosphere. Shown is the absolute response versus wavelength in Angstroms.*

Project Management

We expect that the nominal cost of the project will be \$150M USD, with roughly \$50M devoted to the camera, \$50M to the telescope construction, \$45M to operations and archiving, and \$5M to fund graduate students and a postdoc program dedicated to the SASIR survey. While the longest lead time for this project will be in securing the primary mirror and the 80+ IR arrays, both the telescope construction and the camera can be built in parallel. We expect that a late 2013 first light is a reasonable goal should the project receive significant funding by early-2009. We expect that the survey will be continually manned with no more than three staff astronomers. There will be no guest observers, greatly facilitating a low cost for operating the project. The nightly raw data rate will be about 1/3 Tb, easily reduced and analyzed on-the-fly and transferable worldwide (this translates to a sustained data rate of less than 5 Mb/sec).

The most simplistic survey strategy would be to cover the sky repeatedly with roughly equal time between visits. Over such a 4 year survey, each position could be observed ∼6 times. To determine the parallax and proper motion of objects in the solar neighborhood, we require at least 3 visits per field. In practice, there should be several different cadence strategies, with both competing and complementary goals. For instance, a supernova search would benefit from repeated scans of the same part of the sky every few nights, while a search for high proper motion red stars would require repeat observations on a months–to–years timescale. While we feel strongly that the entire night's sky should be surveyed in at least two IR bands, it is clear that some regions of the sky will be imaged to greater depths than others. Even in non-photometric conditions, the all-sky photometric precision of better than 2% should be very straightforward given the ability to bootstrap off of the brighter stars in the 2MASS survey.

Table 1. Sensitivities of the SASIR Survey

Filter	**Point Source Sensitivity** Single Epoch (5-σ) [AB mag]	[μJy]	Survey (5-σ) [AB mag]	[μJy]	**Extended Source Sensitivity** Survey (5-σ per pixel) [AB arcsec^{-2}]	[μJy arcsec^{-2}]
Y	23.49	1.45	24.47	0.59	23.32	1.71
J	22.95	2.40	23.93	0.97	22.78	2.82
H	22.60	3.30	23.57	1.35	22.42	3.89
K_s	22.47	3.74	23.44	1.52	22.29	4.40

Note. — Based on a preliminary simulation of a four band survey (Y and 2MASS filters J, H, Ks) with 75% clear weather fraction and average seeing of 0.6 arcsec and 18 micron pixels. Each epoch assumes 80 sec total integration with 6 epochs per field over the entire survey (24,000 sq. deg.).

Innovative Mexican/US Partnership in Science & Education

Although this project is motivated by strong scientific goals, we envision a program that will reach well beyond astronomical research. The synergy of UC and Mexico has the potential to impact education at the university and K-12 levels, to inspire the citizens of Mexico and Californians of hispanic heritage to engage in science, to forge new relationships in industry, and to promote new scientific collaborations between UC and Mexico. These broader impacts are as important to the success of SASIR as the science it will produce. It is our goal to establish institutions through the SASIR project in both UC and Mexico that would coordinate and promote these broader activities.

Broader Societal Impact

A gift of astronomy is its ability to instantly inspire and engage the community, both young and old, in science. This is especially true for an imaging telescope whose pictures carry vivid views of our Solar System, Galaxy, and the distant universe. With the construction and operation of a world-class IR telescope in Mexico, SASIR could be a monument and focal point for science to the hispanic community within both Mexico and California. To achieve this (lofty) goal, the community must experience a sense of ownership and participation within the project. Clearly, these activities would require significant resources from the start of the project and a sustained level of activity during the program.

Education

At the university level, we would leverage the existing UC/Mexus program which promotes graduate and postdoctoral research at our institutions. We should aim to develop a concentration devoted to science to renew the tradition of training Mexican astronomers at UC and also promote international collaborations forged around the SASIR project. These efforts should not be limited to astronomy but would include computer science, physics, statistics, engineering and related disciplines with the explicit goal of addressing the shortage of hispanics in science within UC. At the K-12 level, we would initiate projects that would bring SASIR acitivies and science to the classroom. Again, these could be implemented immediately. Consider a 'generation' of students who followed the design, construction, and first-light of this project. One shuld also integrate the science of SASIR in K-12 classrooms, e.g. enable students to write 'proposals' for new (or existing) SASIR observations. For these programs to be successful, we must engage educators within Mexico and the UC who have a strong interest in promoting science within the hispanic community.

Fostering Industrial Connections

Although we do not foresee any special technical challenges in the construction of the SASIR telescope, the project would afford the opportunity to promote new industrial connections between California and Mexico. Co-I Joe Miller, as the UCSC Vice Provost for Silicon Valley Initiatives, is overseeing the conception, development and implementation of the partnerships within Silicon Valley. It is natural to consider this initiative as a path toward the data archival, processing and distribution center for SASIR.

An important goal is to promote the involvement of Mexican industry and the private sector in general in the development and construction of prime scientific facilities. In Mexico this has not occurred in the past as in the United States, and we view it as vital for regional and national development that it be so. Astronomical research can be a platform for offshoots in terms of computer science, telecommunications, engineering, optics and electronics, with substantial impact in economic and social terms beyond the basic science aspect. We will clearly also seek to connect companies of Mexican origin with willing partners within the Silicon Valley.

Beyond simply raising the visibility of SASIR within each of these communities, these activities may be critical to securing funding for the project.

Promoting Scientific Connections

By its nature, the SASIR project is an ambitious observational program whose data products will touch upon many areas of astronomical research. To enhance the impact of these observations, we will aim for the establishment of a SASIR Theory Institute that will encouarge collaborations between scientists in Mexico and the UC. This will include prize postdoctoral fellowships and co-advised PhD students that would split their time among institutions.

The main objective of this proposed Institute will be to improve our understanding of the evolution of the Universe from the Big Bang to the formation of the Earth with emphasis in the processes of galaxy, stellar, and planetary formation. This goal will be pursued along three basic lines: i) the consolidation of the areas of excellence already existing in Mexico with the organization of a wide range of workshops, seminars, and conferences in these areas; ii) the development of new areas for Mexico through the long-term visits of distinguished international scholars in Visiting Sasir Professorships and with the hiring of young promising astronomers from all over the world in Sasir Postdoctoral Fellowships; and iii) the creation of Sasir Scholarships to train young Mexican graduate students in forefront areas of astrophysics within the existing PhD. Astronomy programs at UNAM and INAOE. This combined approach will foster a SASIR center of excellence in Latin America, that will progressively integrate working groups in all modern areas of astrophysics.

In the latin american realm, astronomy is a science of great cultural importance because of the astronomical tradition of the prehispanic civilizations, of the outstanding astronomical sites that are located in the region, and the excellence of distinguished members of this community. The most important astronomical institutions in Latin America are located in Mexico, Brazil, Argentina, and Chile. In particular, Mexico counts with UNAM, systematically recognized in ranking studies as the best university in Latin America. Moreover, citation studies of the impact of research in the sciences made in Mexico consistently shows astronomy as the most relevant one, well ahead of other fields. In addition there is a long tradition in Mexico of collaboration with other institutions in Latin America that have produced significant contributions. For this reason, we believe the presence of a SASIR Institute for Astronomy and Astrophysics in Mexico will become a catalyzer for the development of frontier astronomy in Latin America.

Synergy With Existing Projects and Future Directions

The Mexican astronomical community is a partner in the Gran Telescopio Canarias (GTC) consortium. Furthermore, INAOE is responsible in Mexico for the construction and operation of the Large Millimeter Telescope (LMT), while UC operates the Keck Observatory in partnership with the California Institute of Technology. Thus the potential for synergy with SASIR is great, even already with the facilities at hand, as a large scale survey can naturally provide these general purpose observatories with targets for follow up observations and more detailed study. Keck has proven to be one of the premier optical/infrared observational facilities in the world, and GTC will begin full operations in 2009. The LMT is geared in one aspect to the high redshift universe and so will be able to provide ample follow up information on detections obtained through SASIR.

At the end of the nominal survey, we will maintain a 6.5m telescope with extraordinary wide-field capability at a world-class observing site. There are several paths we might take at this stage. One promising avenue is to develop a fiber-fed spectroscopic instrument that would serve as the 2nd generation SDSS survey. It would push several magnitudes fainter and therefore drive galaxy and quasar research closer to the edge of the universe. Such a survey would impact fundamental cosmology (via measurements of baryonic oscillations), Galactic structure, the study of the first sources in the universe, and reveal new clues regarding the processes involved in galaxy formation.