An Infrared Synoptic Survey for SDSS-V

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Background: In the past decade, surveys of the dynamic sky have revealed a wealth of information in the light curves of eruptive variables and explosive astrophysical transients. The Palomar Transient Factory[1], Dark Energy Survey[2], HyperSuprimeCam[3], and PanStarrs[4] have all deployed CCD-based cameras on telescopes with large etendue (AΩ product), exceeding what the SDSS telescope can likely deliver. In the next decade, LSST[5] and space-based missions[6,7] will dominate the landscape for optical transient astronomy, engaging the US community broadly.

While these facilities will fully exploit temporal information at *visible* wavelengths, studies of the transient sky in the *infrared* have been stifled by high detector costs and a bright sky background. At $0.0012 per pixel, CCDs cost only ~$65k / square degree in detectors to pave large focal planes. The most common IR detectors (Teledyne's HAWAII-2RG[8] or the new H4RG[9]) both cost $0.10 / pixel – an increase of ~80×, or roughly $5.2M per square degree in sensors alone. Add to this the cost of cryogenic optics, colder sensors, and the increased sky background, and the H2RG path becomes prohibitive.

Yet while the optical is powerful for exploration of supernovae and novae, it is blind to transients and eruptive variables that are self-obscured or dust-enshrouded. Moreover the advent of gravitational-wave astronomy – ushered in by Advanced LIGO[10] – has triggered a surge of excitement to discover transient counterparts[11]. Theoretical opacity calculations suggest that the electromagnetic spectra of kilonovae – the expected signature of binary neutron star mergers from radioactive element decay – peak in the infrared and evolve on several day timescales[12,13]. These considerations motivate us to explore a wide-field infrared imager that would position SDSS to play a unique role in the LSST and GW astronomy era.

Infrared Synoptic Science: The threshold science for an infrared transient survey would include novae, supernovae and brown-dwarf transits. This would yield the first true rates of supernovae and novae independent of dust obscuration, and tighten the precision of cosmological constraints from Type Ia supernovae (which have reduced intrinsic scatter in the IR[14]). Recently, a transiting brown dwarf system has been discovered with a 0.6m telescope[15]; with a survey on the 2.5 meter, earth-like planets on brown-dwarfs are easily detectable due to the large relative radii of the planet and star.

We are just now performing the first dedicated IR transient survey (SPIRITS: the SPitzer InfraRed Intensive Transients Survey[16]), which tracks 200 nearby galaxies over two years. This tightly focused project has already discovered 37 infrared transients that have no optical counterparts whatsoever to deep limits with Keck and HST. Interpretation of these new discoveries may include (i) the birth of massive binaries that drive shocks in their molecular cloud[17], (ii) stellar mergers with dusty winds[18,19,20], (iii) 8–10 $M_\odot$ stars experiencing e-capture induced collapse in their cores[21,22], or (iv) birth of stellar mass black holes. SPIRITS reveals that the infrared sky is not just as dynamic as the optical sky; it also provides access to unique and complimentary signatures of stellar astrophysics.

Our baseline science program also looks toward IR followup of gravitational wave events triggered by advanced interferometers. In the early 2020s, the interferometer network will likely include 3–5 stations and deliver median localization of ~10 square degrees[23]. The opacities of Lanthanide elements manufactured in BNS mergers indicate that radioactive decay would power an infrared transient evolving on one-week timescales[12]. Localization of gravitational wave events will provide a critical connection between gravitational astrophysics and traditional electromagnetic diagnostics, addressing for example whether neutron star mergers are primary sites of r-process heavy element synthesis[13].

A significant added benefit is that this survey would gradually build up a deep image of the static sky in the yJH bands in the same hemisphere as SDSS, with comparable spatial sampling as SDSS and substantially greater depth than 2MASS[24]. While the synoptic survey addresses transient science, static yJH imaging in the SDSS footprint would add significant legacy value to the SDSS optical photometric survey. In fact, an IR imager on the SDSS telescope could be competitive in mapping speed to VISTA/VIRCAM, because the low acquisition overheads for the 2.5 meter compensate for its smaller aperture.

Detector Technology: The SDSS telescope's large field of view[25] makes it attractive for synoptic studies, but to reach the ~one square degree minimum size needed to compliment optical time-domain surveys and follow LIGO triggers, a more affordable alternative is needed to HgCdTe CMOS substrates of the H2RG heritage. The H2RG was developed for the ultra-low background application of space-based imaging, and outperforms by far the noise requirements for sky-limited imaging from the ground.

Advances in surveillance technology have driven commercial development of low dark current InGaAs sensors with large format in the last 3-5 years, and our group has been engaged in a development effort to characterize their suitability for astronomy[26,27]. These sensors offer spectral coverage to 1.65 microns (i.e. a slightly shortened *H*) and exhibit higher noise than H2RGs, but at \$0.025/pixel they cost 4× less than HgCdTe sensors of comparable format. We have purchased several small InGaAs sensors and built electronics to sample them in up-the-ramp mode, measuring read noise, dark current, persistence, and photometric stability.

With this setup we have achieved read noise of 43 e- RMS, and dark current at T=-50C of 150 e-/sec/pixel (the dark current halves for every ΔT=-7C). This is far higher than HgCdTe operated at 77K, but sky glow produces [343,1169,3970] electrons per second in the [y, J, H] bands, for a 2.5 meter telescope and camera pixel pitch of 0.5″. We therefore expect that InGaAs sensors can deliver sky-limited performance on the SDSS telescope at four times lower cost than HgCdTe, or \$1.5M in sensor cost per square degree. We have verified that these sensors' persistence is flushed on slewing timescales, and photometric time series show uncorrelated noise on 3+ hour timescales, permitting Poisson-scaled photometric improvement with exposure length. The readout time is a fraction of a second.

This offers the possibility of refitting the SDSS telescope with a sky-limited infrared photometric camera covering the y, J, and H bands, at a rough order-of-magnitude total cost of roughly \$5M for one square degree of active pixels. The band gap of commercially available InGaAs does not permit operation in the 2.2 μm K band, which limits some science applications. However the yJH coverage is well matched to studies of brown dwarfs and kilonovae, and would not require deep cooling (100K) of the camera optics and sensors, thereby reducing cost and technical complexity.

Optical Design and Sensitivity: We have developed designs for a reimaging system that matches our InGaAs detector to the 2.5 meter DuPont telescope at Las Campanas Observatory. This design leverages the DuPont's telecentric optics, splitting the focal plane using a field lens that feeds a "Flys Eye" configuration with small, modular lens barrels for each sensor. Simple modifications should make this design compatible with the SDSS telescope (which is f/5 rather than f/7.5). Because of packaging constraints, the detectors sparsely fill the focal plane, with efficiency between 50% and 75%, to be filled in via incremental pointing offsets. The SDSS telescope's 3° diameter field can accommodate a notional one square degree active pixel area even in a sparsely packed configuration, and the modular nature of the Flys Eye design allows scaling of the field of view up or down as funding dictates.

Sensitivity calculations for a sky limited reimaging camera on the SDSS telescope yield 5σ point source limits for 60 second exposures of [21.2, 21.1, 20.1] magnitudes (AB) for the [y, J, H] bands in a typical synoptic survey mode, or 4–5 magnitudes deeper than 2MASS. For targeted followup of LIGO kilonovae, we would image to depths suggested by models of radioactive mergers situated at the volumetric mean distance probed by LIGO, or m_{AB} ~ 22 in y/J, each of which requires ~5 minutes per pointing for 5σ sensitivity. The camera would have a significantly smaller etendue than optical facilities like ZTF and DECam, but it would cover ~10 square degrees per hour in kilonova search mode and would be a unique dedicated IR time domain facility, complimenting these surveys and eventually LSST.

Next Steps: First, we plan to demonstrate an on-sky proof-of-concept of the InGaAs technology this summer, using already-fabricated optics for the 2.5m DuPont Telescope. Second, we are building a 30cm pathfinder experiment at Palomar that will characterize the bright end of the dynamic infrared sky in preparation for the full-scale survey described here. Optimization of SDSS-V survey depth, cadence, and tiling strategy would be performed during proposal development. Here we simply highlight the potential of the SDSS telescope for a relatively economical yet deep survey of the Northern IR sky, with a synoptic component that is unique among the many time-domain surveys being planned for the next decade.

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