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Findings of the KECK Institute for Space Studies Program on Small Satellites: A Revolution in Space Science

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ABSTRACT

The Keck Institute for Space Studies (KISS) is a "think and do tank" established at Caltech where a small group of not more than 30 persons interact for a few days to explore various frontier topics in space studies. The primary purpose of KISS is to develop new planetary, Earth, and astrophysics space mission concepts and technology by bringing together a broad spectrum of scientists and engineers for sustained scientific and technical interaction. In July and October of 2012 a study program, with 30 participants from 14 institutions throughout academia, government, and industry, was held on the unique role small satellites can play to revolutionize scientific observations in space science from LEO to deep space. The first workshop identified novel mission concepts where stand-alone, constellation, and fractionated small satellite systems can enable new targeted space science discoveries in heliophysics, astrophysics, and planetary science including NEOs and small bodies. The second workshop then identified the technology advances necessary to enable these missions in the future. In the following we review the outcome of this study program as well as the set of recommendations identified to enable these new classes of missions and technologies.

INTRODUCTION

This paper describes the results of a study program sponsored by the Keck Institute for Space Studies (KISS) to explore how small satellite systems can uniquely enable new discoveries in space science. The disciplines studied span astrophysics, heliophysics, and planetary science (including NEOs, and other small bodies) based on remote and *in-situ* observations. The two workshops and study period that comprised this program brought together space scientists, engineers, technologists, mission designers, and program managers over 9 months. This invitation-only study program included plenary and subject matter working groups, as well as short courses and lectures for the public. The objective was to create novel scientific observations, while identifying technical roadblocks, with the vision of advancing a new era of unique explorations in space science achievable using small satellite platforms from 200 kg down to the sub-kg level.

The study program participants focused on the role of small satellites to advance space science at all levels from observational techniques through mission concept design. Although the primary goal was to conceive mission concepts that may require significant technology advances, a number of concepts realizable in the near-term were also identified. In this way, one unexpected outcome of the study program established the groundwork for the next revolution in space science, driven by small satellite platforms, with a near-term and far-term focus.

There were a total of 35 KISS study participants across both workshops from 15 institutions including JPL, Caltech, JA, MIT, UCLA, U. Texas at Austin, U. Michigan, USC, The Planetary Society, Space Telescope Science Institute, Cornell, Cal Poly SLO, Johns Hopkins University, NRL, and Tyvak LLC. The first workshop focused on identifying new mission concepts while the second workshop explored the

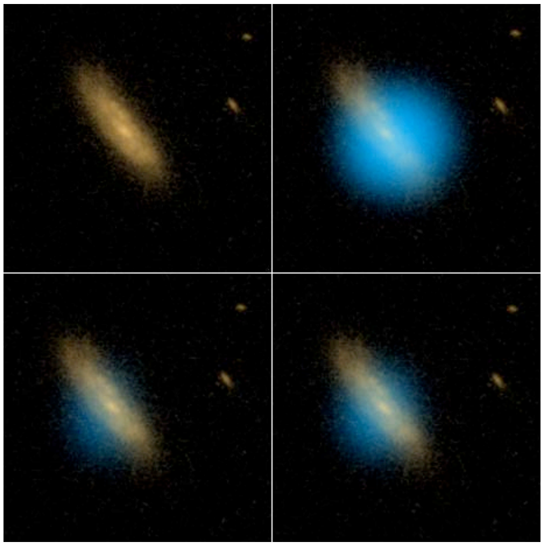

Figure 1: Supernova shock breakout (GALEX).

technology and engineering challenges identified via a facilitated mission concept concurrent design exercise. The Keck Institute limits the number of participants per workshop to at most 30 to encourage close interaction where roughly 20% from this study were students.

DEFINING NEW MISSION CONCEPTS

The first 5-day workshop opened with a short course for the community held at the Lees-Kubota Lecture Hall at Caltech. A keynote talk, by Professor Shri Kulkarni on the "Less Is More Satellite" (LIMSat), is a proposed low mass and low cost small satellite constellation mission of 8 telescopes designed to carry out a wide-field UV transient survey. It is aimed at studying shock breakouts of supernovae producing important science at low risk, see Figure 1. With an instantaneous field of view of 1,200 square degrees (covered by 8 telescopes) LIMSat expects to detect a shock breakout every month. When compared to a mission like GALEX, LIMSat has a sensitivity goal approximately 10 times less with a field of view goal that is approximately 1,000 times larger. If these requirements can be met, LIMSat would have a detection rate 30 times higher than GALEX based on a small satellite design.

Additional talks from the short course covered small satellite functional design, new CubeSat science observations based on NSF's CubeSat-based Science Missions for Geospace and Atmospheric Research program, engineering capabilities of CubeSats and ESPA-class sized small satellites, and mission concepts to address new scientific questions in planetary science concluding with an expert panel on new exploration concepts in astrophysics.

The formal part of the meeting involved a program structured to identify new concepts uniquely enabled by the small satellite platform. Study sessions started with a plenary lead-in talk in astrophysics, heliophysics, and planetary science followed by breakout group discussions on possible scientific observations enabled by small satellites. The groups reported on their progress in the subsequent sessions followed by plenary meetings to begin identification of potential common engineering challenges associated with the new mission concepts.

A partial set of concepts identified is listed in Table 1. The astrophysics concepts are RELIC, SoftX, and UVIP-UV Reionization Probe. These missions were selected to span the spectrum where important scientific discoveries could be made. The heliophysics concepts are MagCon, Solar Polar Constellation, and Fractionated L5 Space Weather Sentinel Constellation. These missions emphasized large-scale first-of-a-kind multipoint physics measurements that take advantage of distributed and fractionated small satellite observation capabilities. The planetary concepts are Champagne, Venus Fly Trap, and Luna Cube. These were largely multi-scale spacecraft systems using a few host spacecraft with hundreds to thousands of picosat observers. (In a separate study period other planetary concepts were explored, including Europa exploration concepts, described in the final report [1].)

ASSESSING ENGINEERING FEASIBILITY

The second 3-day workshop focused on identifying technology gaps and future needs for the broad class of science missions identified from the first workshop. This included plenary discussions on the state-of-the-art in small satellite technology as well as a facilitated mission concept design and concurrent engineering session loosely based on the Team-X mission formulation design approach applied at the Jet Propulsion Laboratory. The L5 Sentinel heliophysics concept was used as a reference mission for this activity. The second workshop also included a public lecture for the community given by Professor Jordi Puig-Suari from Cal Poly San Luis Obispo on "CubeSat: An Unlikely Success Story".

The meeting began with a review of the current technology state-of-the-art in propulsion, power, telecom, instrument, and navigation capabilities with assessment of the technology readiness level (TRL) of such systems. While it was recognized that advances move quickly in this field nevertheless areas where critical technology improvements are needed to enable our mission concepts were identified. These included propulsion and proximity operations, lightweight large deployable structures, deep space power and propulsion systems, communication for Direct to Earth (DTE) transmission as well as for high data rate telecom, navigation, and instrument miniaturization. Such capabilities could be developed within academia, industry, and government. The session continued with a discussion of technology challenges associated with

Table 1: Summary of selected mission concepts in astrophysics, heliophysics, and planetary science.

Missions	Science	Payloads	Approach	Technologies
Relic *Astrophysics*	Understanding energy transport from black holes to the intergalactic medium.	5-meter dipole antennas in all 6-axes. Correlator processors.	Aperture synthesis imaging with a 1 km diameter spherical array of 30-50+ 3U CubeSats imaging doubled-lobed active galaxies at frequencies < 30 MHz.	Formation flying, constellation management, data downlink, antenna deployment, in situ data analysis and correlation management.
SoftX *Astrophysics*	Measurement of the low-energy diffuse background from the interstellar medium.	X-ray spectrometer detector from 100-1000 eV with a single collimator.	X-ray all sky spectroscopy mission in sun-sync orbit observing away from Earth at 1-2 deg. spatial resolution.	Mostly mature. Collimated CCD or CMOS detector and on-board processor for X-ray photon counting.
UVIP-UV Reionization Probe *Astrophysics*	Understanding the source and mechanisms for reionization in the universe.	Arc-second resolution, 912-2400 AA band, ~25cm aperture optics with CCD UV detectors.	UV coarse spectral wide area survey imaging in LEO with a "string of pearls" constellation of ESPA-class small satellites.	Pointing stability, UV coatings, high efficiency UV detectors.
MagCon – Ionospheric/Magnetospheric Coupler *Heliophysics*	Global electro-dynamics of Earth's magnetosphere-ionosphere coupling.	DC/AC magnetometers, Langmuir probe, low-energy plasma instrument, energetic particle and electric field instrument.	In situ measurements by 60 nanosatellites on 6 high inclination orbital planes supported by existing ground assets.	Instrument packaging and miniaturization, EMI/EMC, propulsion, miniature deployment booms.
Solar Polar Constellation *Heliophysics*	First dedicated solar polar constellation mission for understanding variability, dynamo, and Solar System effects.	Heliophysics imager, DC magnetometer, low-energy plasma instrument, energetic particle detector, magnetograph.	Constellation of 6-12 identical CubeSats in high inclination solar orbit.	Instrument miniaturization, high data rate telecom.
Fractionated L5 Space Weather Sentinel *Heliophysics*	Space weather sentinel awareness for predictive modeling from L5.	Heliophysics imager, DC magnetometer, low-energy plasma instrument, energetic particle detector, magnetograph.	Fractionate multiple 6U CubeSats for in-situ fields and particles, heliophysics imager, magnetograph and telecom at Earth-Sun L5 using solar sails.	Propulsion capability and station keeping at L5, relay communication, instrument packaging and miniaturization, arc-minute pointing stability.
Venus Fly Trap *Planetary*	Detailed investigation of Venus' zonal wind flow activity.	ChipSat and thin-film detectors with atmospheric sensors.	2 Mother spacecraft (ESPA-Class) with 100s of daughter spacecraft (ChipSat-Class) for differential doppler tracking.	Differential Doppler tracking, instrumentation, swarm communications.
Champagne *Planetary*	Determine spatial, velocity distribution, and physical properties of planetary rings.	ChipSat accelerometers and thin-film large apertures.	Insert 10,000+ ChipSat and smaller 10s+ of CubeSats into ring structure for particle inspection and characterization.	Propulsion, tracking, telecom, extreme environment survivability.
Lunar Cubes *Planetary*	Lunar interior mapping and volatile characterization.	Micro seismometers.	ChipSat and/or CubeSat scale hard landing instruments transmitting continuously to on-orbit spacecraft observers.	Lunar environment survivability, impact survivability.

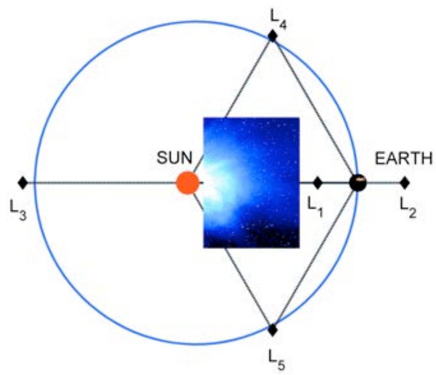

Figure 2: Earth-Sun-L5 schematic showing coronal mass ejection from heliospheric imager instrument on STEREO [2].

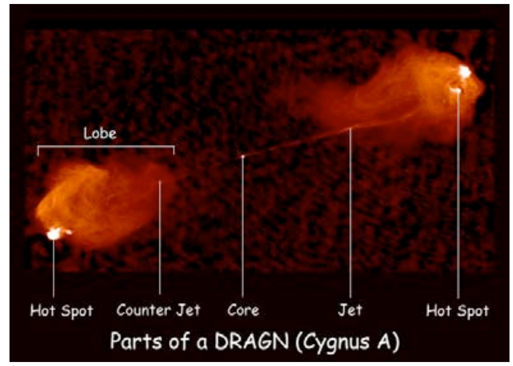

Figure 3: VLA image of a strong Double Radio Sources Associated with Galactic Nuclei (DRAGN) of the Cygnus A radio galaxy [A. Bridle, NRAU].

Entry, Descent, and Landing (EDL) of small satellite systems relevant to new mission concepts that might be pursued at Mars, Europa, Titan, and other vistas. Technology advances for lightweight deployable structures were presented, as well as advances in on-board processing technology and approaches for resiliency within the space environment. The study group also heard about new advances in ChipSat and thin-film technologies for lightweight and low ballistic coefficient miniaturized spacecraft for landers.

The main product of the concurrent engineering exercise was subsystem group performance analysis leading to mass and power budget estimates, as well as cost, given the proposed L5 Fractionated Space Weather Sentinel reference mission [2]. Examining the science objectives and establishing the operational modes the fleet of spacecraft would perform achieved this objective [1]. This included analysis for all of the major subsystems including the ADACS, command and data handling, power, propulsion, structures and mechanisms, cabling, telecom, and thermal analysis with margins. While the group did not have access to all of the analysis capabilities typically associated with a JPL Team-X concurrent design exercise, there was sufficient experience and engineering judgment to allow the group to close on an assessment of the concept as well as the technical challenges required to achieve the mission. A potential 6U CubeSat bus was proposed for this solar sail based mission concept. The experience also served as a pathfinder for future exploration of the remaining mission concepts.

A CLOSER LOOK – RELIC

RELIC was one of the astrophysics missions conceived during the study to understand energy transport from black holes to the intergalactic medium. This mission concept creates a very low frequency (5 – 50 MHz) large constellation array of radio antennas to image galaxies to observe relic radio halos that remain long after radio outbursts, see Figure 3. In general, such low frequency astronomy observations are best performed well above Earth's Ionosphere with distributed antennas so it's a good fit for spaceborne observations.

This concept would utilize 50-100 small satellites deployed in a spherical geometry ~1 km in diameter located far from Earth (likely in an Earth trailing orbit or a lunar quiet zone). Each spacecraft would carry 6 dipole antennas with receivers in the +/-x,y,z coordinate directions communicating with a host spacecraft to correlate signals and to facilitate transmission back to Earth. Deployment of the configuration would be via an ESPA-ring based spacecraft that would contain multiple high gain antennas for continuous transmit capability. There would be booms for docking of the individual science spacecraft in the constellation to support services including autonomous assembly and repair, with backup spacecraft, should a catastrophic failure occur.

Technology advances in formation flying, signal processing, communications, autonomous assembly, propulsion, and other areas would be required. Nevertheless the significant number of observing systems would give a new and first of a kind insight into this observation.

OUTCOMES AND RECOMMENDATIONS

Forming a community that established the existence of new scientific observations of merit, uniquely enabled by small satellites, was a key outcome of this study. Although technology challenges were identified some near-term concepts are actively being developed and proposed for future mission opportunities. Most of the science concepts created during the study program will require specific technology advancements that must

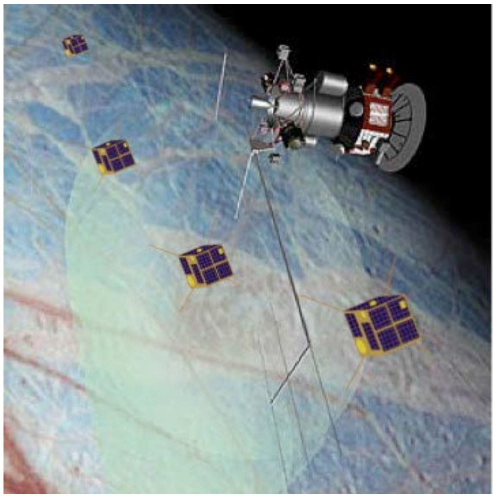

Figure 4: Potential vision of SmallSats collaborating with deep space planetary missions.

occur over a period of years, and perhaps decades such as compact ASRG power sources, radiation hardened deployers and components, and so on.

To enable the vision established by this report, Figure 4, some of the study team recommendations include:

1. **Beyond LEO SmallSat Scientific Exploration Program**: Development of a set of scientific objectives, and roadmaps, tailored specifically to unique small satellite observations in astrophysics, heliophysics, and planetary science.

2. **Deep Space SmallSat Technology Maturation Program**: Development of system hardware and software capabilities to enable long duration and resilient small spacecraft systems.

3. **SmallSat Launch and Operations Program**: A program specifically tailored to support launch and operations capabilities for constellation spacecraft systems emphasizing beyond LEO operations. This includes investments in ground station capabilities and associated infrastructure to support deep space telecom.

4. **Small Spacecraft as Secondaries on All Beyond LEO Missions**: Establishing this capability adds value to flagship mission science observations, specifically where measurements are desired in extreme environments, or regimes deemed excessively risky to the primary.

NEXT STEPS

Many of these concepts are moving forward in various directions. The SoftX astrophysics concept is in proposal evaluation as a potential mission. Mission studies have been held for the MagCon Heliophysics concept while the L5 Fractionated Space Weather Sentinel concept will be presented at the 3rd International Solar Sail Conference [2]. A variety of spin-off topics are being explored related to deep space observations for collaborative, constellation, and stand-alone missions within JPL, and elsewhere, for planetary science utilizing SmallSats. Sessions on this subject are being formed within traditional scientific conferences.

The final report, with much greater detail on the study, is available at the Keck Institute for Space Studies site http://www.kiss.caltech.edu/study/smallsat/. It provides direction for technology capabilities relevant to development of these future missions concepts as well as the kinds of unique science observations enabled by these platforms. While not exhaustive, the long-term impact of this study has been to set a strategic direction and to initiate the conversation on how SmallSat platforms can enable a new class of scientific discovery this is relevant, unique, and cost effective.

Acknowledgments

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References

1. C. Norton, S. Pellegrino, M. Johnson, et al., “Small Satellites: A Revolution in Space Science” to appear as final report to the Keck Institute for Space Studies.

2. P. Liewer, A. Klesh, M. Lo, N. Murphy, R. Staehle, V. Angelopoulos, B. Anderson, M Arya, S. Pellegrino, J. Cutler, E. Lightsey, and A.

Vourlidas, “A Fractionated Space Weather Base at L_5 using CubeSats and Solar Sails” to appear, 3rd International Symposium on Solar Sailing, Glasgow.