Astro2020 APC White Paper

The Enabling Capabilities of the Super Pressure Balloon Platform: Diffraction-Limited, Wide-field Imaging from the Stratosphere

Thematic Areas:
Sub-orbital Project

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Key Science Goals and Objectives:

The activities addressed in this paper directly address the thematic area of Cosmology and Fundamental Physics, with secondary application to a wide range of science goals that are highlighted in the Science White Papers submitted to the current Survey. The stratospheric balloon borne imaging telescope, SuperBIT, has recently demonstrated near diffraction-limited, wide-field imaging in the near ultra-violet (NUV) to near infrared (NIR) wavelengths [1, 2]. This White Paper describes the scientific potential and technical approach of a 1.5 m class observatory that will i) improve the accuracy and precision of cosmology using galaxy clusters through improved constraints on mass-observable relations, ii) serve as a force multiplier for LSST, WFIRST and Euclid, and iii) enable a better understanding of the evolution of the expansion rate of our Universe and the dark energy equation of state. A persistent, wide-field sub-arcsecond imaging capability between 300–1000 nm provides the ability to perform de-blending as well as the stable, well calibrated photometric redshifts that are specifically called out as high priorities in the *Dark Energy & Modified Gravity* [3] and *Euclid/LSST/WFIRST Joint Survey Processing* [4] Science White Papers. The general imaging capability has further application to a wide range of disciplines within astrophysics and planetary science [5], as demonstrated by the enormous productivity and over-subscription of Hubble's WFC3 and ACS instruments.

The Hubble Space Telescope is the currently only observatory capable of providing wide-field imaging with angular resolution less than 100 milli-arcseconds (mas), at wavelengths from the near-UV to near-IR. The leading terrestrial observatories employ multi-conjugate adaptive optics (MCAO) to achieve comparable (or even superior) angular resolution, but over very small fields of view (of order an arcminute), and at longer wavelengths. Hubble's functional lifetime is limited, and costs nearly $98 million dollars a year to operate.

For over twenty-five years, the unique capabilities of the Hubble Space Telescope (HST) have enabled a continuous stream of discovery and inspiration for the scientific community and the public alike. The scientific potential of Hubble is such that, over the last three years, observation time has been over-subscribed by a factor of six or more. During this period, nearly 60% of the allocated time was devoted to the operation of the wide-field imaging cameras (WFC3 and ACS) operating at wavelengths from the near ultra-violet (UV) to the near infrared (IR).[1]

In this paper we describe a stratospheric balloon-borne observatory whose wide-field imaging capability far exceeds that of Hubble, expanding on that heritage of discovery at a fraction of the operational cost. It is likely that the Hubble will reach the end of its operational lifetime in the coming decade. NASA's next generation space telescopes, including the James Webb Space Telescope and WFIRST, will provide extraordinary new capabilities but operate at longer infrared wavelengths; they do not fully replace or extend the capabilities of HST that are most in demand.

Wide-field, sub-arcsecond imaging will enable weak and strong gravitational lensing studies that will reveal the distribution of matter in and around galaxy clusters with unprecedented resolution and accuracy. Performed over a large ensemble of clusters spanning a wide range of evolutionary stages, these measurements will revolutionize our ability to understand the role of Dark Matter in the formation and evolution of the cosmic web, while providing crucial insights into the physical properties of this enigmatic substance. Nevertheless, the scientific reach of the observatory is much more broad. Ultimately, the objective is to operate the telescope as a facility

[1] HST selection statistics: `http://www.stsci.edu/hst/metrics/SelectionStats`

instrument, with the majority of its observation time devoted to the competitively selected general observing proposals, bridging a gap in NASA capabilities for the foreseeable future.

Technical Overview:

Long duration, mid-latitude stratospheric balloon flights provided by NASA's Super Pressure Balloon platform (SPB) represent a transformative capability within NASA's Balloon Program. A sustained program of development for this technical capability, with corresponding support of payloads that can realize the scientific opportunity it affords will both support the development of a diverse pool of highly qualified personnel and provide capabilities that surpass those of the great observatories, all at a fraction of the cost of a flagship mission.

For the past several decades, the Antarctic Long Duration Balloon (LDB) program has provided large payloads (science payloads up to 3t) access to altitudes above 32 km for flights as long as a month. This program has driven scientific advances in numerous fields, including the establishment of the standard ΛCDM model of cosmology (Boomerang $\rightarrow$ Planck HFI, a new window on high energy cosmic rays (SuperTIGER) , enabling advances in x-ray (HEFT$\rightarrow$NuSTAR) and gamma-ray (COSI) astrophysics.

While the Antarctic flights provide access to a limited portion of the southern sky with the Sun always above the horizon, mid-latitude LDB flights can access nearly the whole sky, providing extended periods at float altitude in both night- and day-time environments. As such, the scientific opportunities enabled by the SPB platform are largely complementary to those of the Antarctic LDB, and will open as many new opportunities as the Antarctic LDB program did two decades ago.

NASA's balloon research capabilities were carefully studied in the context of the NASA Authorization Act of 2008, in which an ad-hoc committee of the Space Studies Board of the National Research Council was charged with providing a detailed assessment of NASA's sub-orbital program. A principle recommendation of that study was that "NASA should make essential investments in stabilizing and advancing ... the development of ultra-long-duration super-pressure balloons with the capability to carry 2 to 3 tons of payload to 130,000 feet ..." [6].

With the rapid growth in the technical capabilities of science payloads, the justification for this recommendation has only grown stronger in the past decade. However, from an operational point of view, the goals laid out that study have not been fully realized. Since 2015, NASA has made three mid-latitude test flights of the 18.8 million cubic foot (MCF) super-pressure balloon, which can accommodate a science payload mass just over 1 ton.

This white paper briefly describes the impact of the super pressure capability on an application that directly addresses themes highlighted in the Science White Papers: diffraction limited, wide-field imaging between $300 < \lambda < 1000$ μm.

While considerable progress has been made on the development of the SPB platform, more focused investment in its development is required to advance the state of SPB operations to that of the Antarctic LDB platform allowing not only the realization of the scientific potential of this imaging capability, but also that of numerous other applications to planetary and astro-particle sciences.

The specific activities advocated for in this White Paper support those addressed in the report submitted by the Balloon Program Analysis Group [7], and include increased support and prioritization of:

- A regular cadence of long duration SPB launch opportunities from a mid-latitude site (Wanaka, NZ).
- Infrastructure to support LDB payloads (integration facilities, launch vehicles) of size and complexity comparable to the LDB program.
- Training and support of the launch crews necessary to support multiple annual campaigns.
- Development of technologies/procedures for supporting increased science mass on the SPB platform.
- Development of improved telemetry rates and commanding.
- Development of payloads, including facility class observatories, to realize the scientific potential of the SPB platform.

Technology Drivers:

We propose the development of a stratospheric balloon-borne observatory whose wide-field imaging capability far exceeds that of the HST, expanding on its heritage of discovery at a fraction of the operational cost. Hubble is reaching the end of its operational lifetime. NASA's next generation space telescopes, including the James Webb Space Telescope and WFIRST, will provide extraordinary new capabilities but operate at longer infrared wavelengths; they do not fully replace or extend the capabilities of HST that are most in demand. At the same time, the demand for sub arc-second resolution imaging to complement the numerous large terrestrial programs, such as LSST, will grow exponentially as these ambitious programs begin.

In astrophysics, location is everything; the exceptional capabilities of HST derive largely from its unique vantage point in space. Earth's atmosphere attenuates astrophysical signals, smears resolution through turbulence, and introduces instabilities in the calibration of terrestrial observatories. Furthermore, there is never any weather in space, leading to a very high duty cycle of observations.

In a series of three flights, SuperBIT has directly characterized the observing environment at optical wavelengths at altitudes between 30.5 and 36 km. Throughout this range, the optical backgrounds remain exceedingly low and there is no evidence of seeing from the residual atmosphere at the level of 100 mas[2].

While the balloon platform offers access to a near-space environment for a few percent of the cost of an orbital mission, it does present several technical challenges. In particular, the dynamic instability and thermal environment of the balloon platform make deep sub arc-second imaging extremely challenging. However, with the support of three years of NASA APRA funding[2], SuperBIT has successfully flown on two test flights from NASA's scientific balloon facility in Palestine, Texas. During an overnight flight in June 2018, SuperBIT demonstrated the ability to obtain deep, near diffraction-limited, wide-field imaging from the near-UV to the near-IR [2]. SuperBIT employs a coarse ($\sim$ 1 arc-sec) pointing system to point the telescope and provide field rotation for 30 minute exposures. The fine pointing system uses a fast tip/tilt mirror using feedback from an array of fiber optic gyroscopes and a guide camera.

[2] SuperBIT has been developed under a NASA APRA grant NNX16AF65G, NSERC, the CSA and Durham University

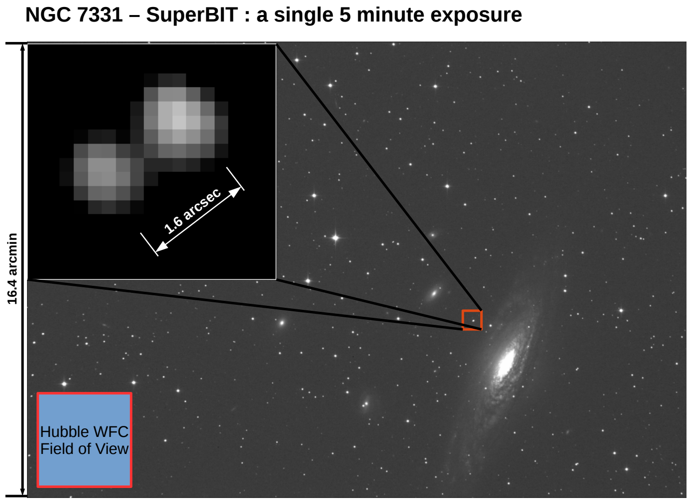

Figure 1: A demonstration of the resolution and field of view achieved during the 2018 test flight of SuperBIT. The image shown, in the vicinity of NGC 7331, is a single five minute exposure at 500 nm, using a prototype 0.5 meter aperture telescope. The Hubble WFC3 field of view is shown for scale. The inset demonstrates the potential for de-blending of future ground-based survey data using stratospheric diffraction-limited imaging.

This system, using a prototype 0.5 meter aperture f/10 telescope, achieved sub-pixel (150 mas) stability on the guide camera during extended exposures of the 29 Megapixel science camera. SuperBIT employs a seven-position filter wheel, with demonstrated imaging in five photometric bands between 300 nm and 1000 nm, and a wide shape-band at 500nm. [3] An example of the imaging capability, obtained during the 2018 test flight, is shown in Figure 1. In addition to the imaging, SuperBIT's test flights have demonstrated all the sub-systems required (fine pointing system, focal plane instrument, thermal control, power systems, flight control, data storage) within the mass envelope (roughly 1 ton) for a long duration science flight.

The SuperBIT data provide a clear path forward for a diffraction limited 2 meter class observatory. While improvements are required in the mechanical and thermal stability of the optical system, they represent incremental improvements from SuperBIT's proven approach. The principle challenges in scaling up from SuperBIT's 0.5 meter aperture include i) the development of a lightweight telescope of sufficient optical quality to remain diffraction limited in the near-UV, ii) the development of in-flight collimation capability necessary to maintain the system diffraction limited through the day/night thermal cycle, and iii) upgrading the fine pointing system to provide the necessary bandwidth and flexibility in the selection of suitable guide stars.

A design study has been performed of a folded, on-axis three-mirror anastigmat (TMA), using a silicon carbide primary and tertiary both to reduce weight and improve thermal stability of the 2 meter system. The TMA layout provides a large diffraction limited field of view (roughly 2 square degrees), and allows for a large measure of flexibility in the selection of science instruments. The baseline configuration would include a dichroic beam-splitter to feed NUV and NIR optimized imaging cameras. Depending on the cost and schedule impact, a near-UV imaging spectrometer could be considered along side the imagers. The quality of the mirror surface and the surface coatings drives the cost of the optical system, but no new development of capabilities or techniques were identified during the coarse of the study. Techniques for performing in-flight collimation and alignment compensation of the TMA will require some modest development relative to the state-of-the-art. Leveraging the rapid advances in imaging technology since Hubble's last upgrade, the 2 meter system will image a given area of sky to a given depth as much as forty times faster than

[3]The seventh filter position has been configured with an H_α filter.

Hubble at wavelengths between 300 and 1000 nm. This represents the capability that is in highest demand from the scientific community.

Organization, Partnerships, and Current Status:

The development and demonstration of this capability are best achieved as a relatively small and nimble university led collaboration, as are supported through NASA's APRA program. However, once entering operation as a general observing platform, the operations and management will require a larger, more formal structure including a time allocation committee, efficient observational support and, importantly, enable timely upgrades to the instrumentation. The latter capability represents a significant advantage of the sub-orbital platform over an orbital facility.

SuperBIT is a collaboration between Princeton University, the University of Toronto, the Dunlap Institute, Durham University and the Jet Propulsion Laboratory. SuperBIT's flight operations are supported through APRA NNX16AF65G, and includes support for a long-duration SPB science flight.

Schedule:

Subject to the operational development of the SPB platform, a 2 meter class observatory could be put in service by mid-decade. This is possible due to the heritage of NASA's investment in the APRA program, which continues to serve as a cost effective incubator for emerging capabilities and technologies.

Cost Estimates:

Based upon the actual costs of SuperBIT (approximately \$2M, in current year dollars) and the optical design and cost study for the 2 meter class telescope described above, this capability could be demonstrated with the small sub-orbital cost category (<\$20M). The primary cost drivers include the fabrication and coating of the telescope, and the associated low-mass mechanical structure (\$4M), the fine pointing control components, including fiber optic gyroscopes and star cameras (\$1M), and the light-weight gondola and course pointing system (\$2M). A modest focal plane instrument that is well suited to demonstrate the imaging capability on a test flight would not drive the project cost. This scale falls just within the scope of the APRA program, albeit on the high end of what can be fit within a five-year program. The re-imaging optics and focal plane instruments that would be required to fully realize the potential of the observatory would require a significantly higher investment (\$8M), but would still fit comfortably within the small project cost category.

NASA's Balloon Project operates on a budget of approximately \$40M/year (in 2020), most of which is devoted to supporting operations [8]. A more detailed discussion of the balloon program and budget can be found in the submission from the NASA Balloon Program Analysis Group [7].

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