Sub-Orbital Large Optics Observatory (SOLOO)
Astrophysics and Planetary Science

Overview:

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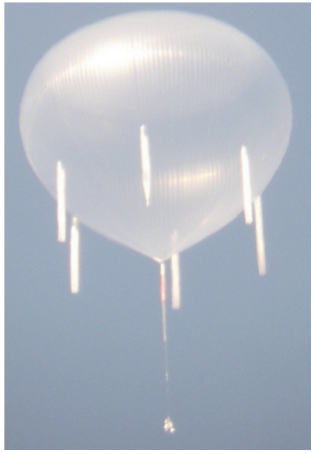
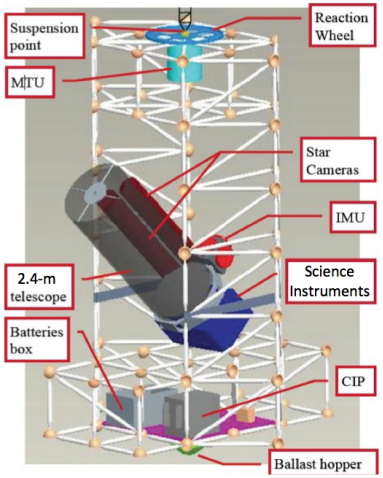
Key Collaborators: GSFC, Wallops, JHU/APL

Goals: Provide a Hubble-class observatory to the astronomical and planetary science community, at low cost to NASA





NASA's Ultra Long Duration Balloon with AFTA Telescope based payload

Description:

Concept and Implementation: Develop a suborbital (ultra-long duration balloon) payload using the Large telescope optics, as a community resource. The observatory can be flown repeatedly for months at a time using different competatively selected instruments or for different research goals. The observatory will be capable of diffraction-limited imaging and spectroscopy in the optical and Near-infrared and, with a coronagraph, high contrast exoplanet imaging.

Observations: The SOLOO addresses a range of Decadal Survey science priorities such as observations of exoplanets, active galactic nuclei, Galactic and extragalactic stellar objects, galaxies in the early universe, and solar system bodies. The prime science emphasized here is coronagraphic observations of planets around nearby stars.

Technology readiness: Pointing control to enable diffraction limited imaging appears to be in-hand (Wallops WASP system, and system developed at JHU/APL). A gondola that insures safe payload landing needs to be developed based on existing technology. Payload capacity relative to observatory mass is a concern that needs further study.

External collaborations: Instruments could be donated by international collaborators.

Human Exploration utilization: none

Value to NASA:

Budgets for SMD, as well as NASA as a whole, are constrained so we need to consider innovative new ways to use the second set of Large space optics. A suborbital (balloon) application would cost only a fraction of that for a fully qualified space observatory, and yet is capable of providing space-based performance. Combining these assets together with NASA's Ultra-Long Duration balloon program promises the following advantages:

- Low-cost development and operations
- "Hubble-class" performance at optical and Near-IR wavelengths to address Decadal priority science
- Repeated flights of several months duration each
- The whole US and international community participates
- New technology instruments could be developed, flown and validated before being used in future space missions
- Allows much more frequent access to space than the current ~15 years between flagship missions

A Sub-Orbital Large Optics Observatory (SOLOO) using the Large Space Optics

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Qualifications: Dr. Lyon is an astrophysicist and optical scientist at GSFC. He is the lead scientist for development of the Visible Nulling Coronagraph, and a coronagraph expert. He has recently led a concept study for a suborbital telescope for exoplanet observations.

Contributing authors: Members of the Astrophysics and Solar System Divisions at NASA/GSFC, and the Balloon groups at Wallops Flight Facility and the JHU Applied Physics Lab. The latter two groups have developed and tested precision balloon pointing control systems.

Primary Concept Goal Category: Astrophysics (also Planetary Science and space technology)

Concept Summary: We propose a low-cost option for use of the large space optics in a suborbital (balloon-borne) astrophysics observatory. This would be a *community* resource managed by NASA's suborbital program office, with investigators building competitively selected instruments for flight. A broad range of exciting astrophysical and planetary (solar system) science would be enabled, while also providing a platform for testing new instrument technologies for future space missions.

We envision long suborbital flights using NASA's Ultra-Long Duration Balloon (ULDB), payload recovery, and re-flights using different instrumentation.

Goal of Concept: NASA will be operating with constrained resources for the foreseeable future. In such an environment, we need an innovative option to make good use of the high quality optical telescope assemblies (OTAs) donated to NASA, if funds are not available for a multi-billion dollar space mission. Recent improvements in suborbital balloon technologies – including sub-arcsecond pointing and super-pressure balloons that can fly at the 130,000 ft level for months at a time – make a SOLOO a very attractive option.

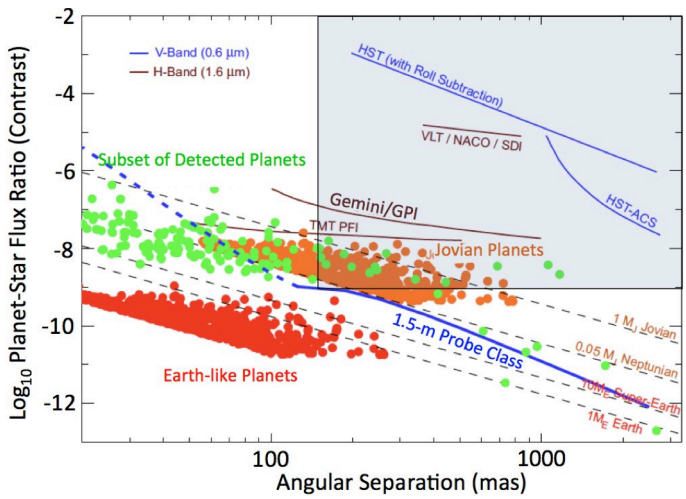


Figure-1: SOLOO will image dust disks, constrain their models, image Jovian & large planets, potential superEarths, refine orbital elements and ultimately perform spectroscopy to characterize planetary atmospheres around F, G, K-stars. Multiple flights (up to 100 days each) allows for successive generation instruments such as an IFU and polarimetry. SOLOO will operate at inner working angles of >3 $\lambda/D \sim 0.15$ arcsecs in V-band to a processed contrast of 10^9 (region in grey) allowing many Jovian detections. Above Jovians/Earth planets are model based.

Table-1: Exoplanet Questions that SOLOO could answer

Priority	Science Topic	Exoplanet Questions that SOLOO Addresses
1	ExoZodi Brightness	What is the range of exoZodiacal brightness versus range of star systems ages ?
2	ExoZodi Features	Do exoZodi features correlate with the location of planets. Does surface brightness vs disk location agree with models ?
3	Exoplanet Imaging	Exoplanets at location of dust resonances, range of orbital parameters, contrast limit bound on planets in Habitable Zone (IWA=142 mas => HZ imaging of Sirius A, Vega, Fomalhaut, Altair, Alpha Centauri A,B, Procyon A, Tau Ceti), "Exclusion principle" to image gas/large planets that dynamically preclude HZ planet formation.
4	Exoplanet Spectroscopy	How different are the planets atmospheres from planets in our solar system. Characterize planetary atmospheres - do biomarkers exist ?

SOLOO would achieve diffraction-limited imaging from a combination of observatory-level pointing control (star-trackers, reaction wheels), a fine steering mirror within the instrument to mitigate jitter, and a deformable mirror (DM) to correct wavefront errors. SOLOO would then be an easily serviced equivalent of a wide-field Hubble Space Telescope (albeit

with limited capability in the ultraviolet). Science would be determined by competitive instrument selection and a guest observer program and could make new scientific discoveries in:

Table-2: Illustrative SOLOO Mission and Instrument Parameters

Sub-Orbital Large Optics Observatory (SOLOO) *Brightness & Morphology of Dust Disks and detection/characterization of exoplanets*		
Theme	Origins of Life in the Universe	Characterize dust disks to facilitate exoplanet science.
Primary Goal	Further understand nature of dust/debris disks and exoplanets. Constrain models.	Disk luminosity, morphology vs feature size vs age vs spectral class in disks.
Targets	Bright Local Stars	>20 targets, stats vs age, spectral class.
Launch Date	July 2018 but TBD	Assess targets and technology for >2020 missions.
Lauch Vehicle/Lifetime	ULDB Balloon / multiple 100 day flights. Safe recovery w/ 'beef up' gondola with water floats.	Antartic, or New Zealand, launch.
Payload Mass	< 2500 kg (estimated)	ULDB's with up to 2300 kg have flown
Field of Regard / View	20° - 65° Elevation, 30 arcsec square FOV	Nyquist sampled (λ/2D), photon counting detector
Pointing Control	Star trackers to 1 arcsec	Fine Steering Mirror (FSM) to <12 mas
Inner Working Angle / Contrast	Reqmt: IWA = 0.15 asec (3 λ/D), 10^8 Contrast	Goal: IWA = 0.10 asec (2 λ/D), 10^9 Contrast
Sensitivity	Reqmt: 3 Zodi's	Goal: 1 Zodi
Wavelength	Visible Light	4 filters R = 9.2
Telescope	2.4 meter, on-axis obscured, glass, w/ SM control & steering	Temperature held at 20°C
Technologies	precision pointing, GSFC Visible Nulling Coronagraph and other coronagraphs.	Technologies at or above TRL-6 except MEMS DM (TRL-4). Contrast 10^9 achieved w/ VNC, VNC held @ 20°C
Power	< 1400 W	Warm PM/SM + cold camera
Comm & Data Rates	LOS link and TDRSS	1 Mbit/sec, 150 kbit/sec, broadcast 24/7
Integration & Test	Telescope & coronagraph @GSFC	Plum Brook B-2 Chamber Test
Expected Costs	To preliminary to cost with any confidence.	<$200M ?

Exoplanetary systems: The contrast achievable by the 2.4m OTAs is not completely understood at present; however, contrasts of 10^9 (10^8 raw, 10^9 processed) to inner working angles (IWA) of 3 λ/D = 142 milli-arcseconds (mas) should be achievable in visible light (Fig-1 grey box) to progressively answer the questions in Table-1 via the high-level mission in Table-2. This would allow the study of debris disks around stars, as well as the discovery and characterization of Extrasolar Giant Planets (EGPs). Critical to this understanding is the assessment in terms of those spatial frequencies that scatter light into the imaged region of the planet. If contrasts of 10^{10} are achievable, then massive, or superEarths, exoplanets in nearby star habitable zones could be imaged (complementing JWST transit spectra). As the number of transiting exoplanets discovered continues to quickly grow, it will be important to characterize their atmospheres spectroscopically. This is difficult to do from the ground, due to photometric variability, turbulence, scintillation and scatter caused by Earth's atmosphere. At 130,000 feet altitude SOLOO will be able to perform these important observations (Fig-2), and with high-contrast coronagraph capability that HST does not have.

Galaxy Evolution: SOLOO's wide field of view is well suited to spectroscopic surveys of galaxies at intermediate to high redshift for the purpose of determining galaxy properties, such as metallicity, age, mass, and internal dynamics. The near-IR sensitivity of SOLOO allows the study of the important redshift range of z=1-2, the peak of the galaxy construction era. This is an area of science not pursued by WFIRST (instrument spectral resolutions are not high enough to determine these galaxy properties – it has low resolution spectrographs to determine galaxy redshifts and coarse supernovae spectral features).

Solar System: A wide-field diffraction-limited telescope has many applications for studying solar system bodies. Young[1] has emphasized several studies: (1) long-term monitoring of atmospheres of giant and ice planets in the visible. Weeks of continuous monitoring are crucial for our understanding of the weather patterns on the planets (Note: HST does not have the resources to support such long-term monitoring); (2) search for and characterization of asteroids and Trans-Neptunian objects (TNOs). The high spatial resolution of SOLOO would resolve

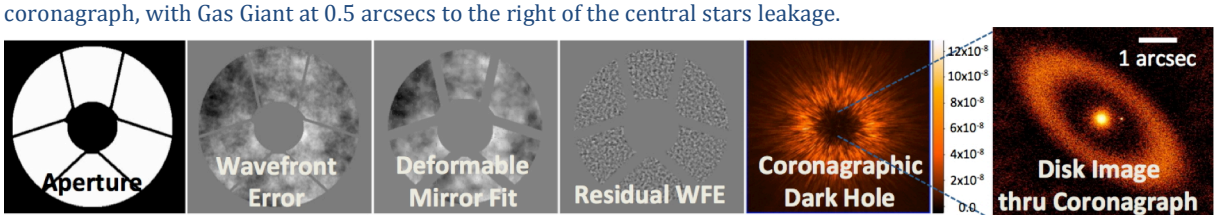
[1] Young, et. al., *Balloon-Borne Telescopes for Planetary Science: Imaging and Photometry*, White paper to Solar System NAS Decadal Survey (2012)

these objects to determine the fraction that are binaries, and shed light on their origin; and (3) a search for Near-Earth Objects (NEOs), providing higher sensitivity and also better astrometry.

Benefits of the Concept: The SOLOO concept provides access to wide-field, diffraction-limited imaging and spectroscopy from near space (above 99.5% of earth's atmosphere) at a fraction of the cost of a space mission. The observatory could be flown for months on ULDB platform, and re-flown with different instrumentation on each flight. Such instruments would be competitively selected and engage the community, and provide beyond HST science capability.

Technical Description of Concept: At balloon altitudes the residual atmosphere is less limiting than for ground telescopes. The turbulence spatial scale (Fried parameter) is the outer scale (few meters to 10's of meter) of the atmosphere, i.e. where solar energy couples to the atmosphere, and results in low-order wavefront errors (tip/tilt, focus, astigmatism, coma etc.). The coherence time would be << 1 Hz implying a slow drift in low-order wavefront errors. These errors would be managed via secondary mirror actuators, a fine steering mirror, and a deformable mirror that all coronagraphs must have. The fine steering mirror would also compensate for higher frequency pointing jitter. Wavefront control would ultimately be dominated by thermal drift inducing optical misalignments and deformations. The telescope and instruments would be assembled, integrated and tested on the ground at near room temperature. Active heaters would keep the observatory at a stable temperature – actual temperature is not critical, only stability per observation at the chosen temperature. Quick estimates show <1400 Watts would be needed to hold temperature - achievable with standard solar panels that routinely fly on balloons. Further analysis and modeling is required for a comprehensive design. With the proper thermal design

Figure-2: *Image Simulation with SOLOO*. Left to right: panel1 is NRO telescope aperture, panel 2 a random wavefront error, panel 3 is the deformable mirror fit, panel 4 the residual uncorrected wavefront error, panel 5 the dark hole focal image for V-band [500-600 nm]. The simulated dark hole is 2 arcsec in diameter with contrasts from 10^{-8} to 10^{-9} (lower left plot) within dark hole and $\sim 10^{-7}$ outside it. Right panel shows a simulated disk image, through a coronagraph, with Gas Giant at 0.5 arcsecs to the right of the central stars leakage.



and with active thermal and pointing control systems, that SOLOO would have the capability of operating at the diffraction limit. Balloon pointing control has achieved the necessary pointing[2,3]; existing systems would need to be scaled for the increased observatory mass.

A balloon payload sees a benign launch environment–with launch shock at the outset and during descent/landing. Re-use of SOLOO requires a gondola that allows soft landings on land and water. Water landings are feasible using helicopter emergency landing floatation devices; ground landing can be softened by encasing the telescope within the gondola with shock absorbing pads on all sides of it. Further work would be needed to develop a viable re-usable gondola; but this is a cost and schedule issue, and, gondola development costs are low relative to technology development costs for a space flight mission.

SOLOO's compelling science is achieved at a fraction of the cost of a comparable space mission. It advances space technologies, acts as a near-space technology test platform and re-using it allows one NRO telescope to operate as a community wide science resource.

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[2] http://www.nasa.gov/centers/wallops/news/wasp.html

[3] C. Martin, P. Bernasconi, et.al , *Terahertz Ballooning: STO and GUSSTO Mission Concept*, AAS Meeting #220, #134.09 (2012)