

White Paper for NASA 2021 Decadal Survey

Title of the white paper: STRATOSPHERIC BALLOON PLATFORMS FOR PLANETARY SCIENCE

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STRATOSPHERIC BALLOON PLATFORMS FOR PLANETARY SCIENCE. T.

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Science Enabled from High Altitude Balloons: Balloon-borne platforms for planetary science observations can play a key role in addressing numerous outstanding decadal-level science questions. Long used for studies that have advanced our understanding of astrophysical and heliospheric phenomena, balloon-borne investigations have heretofore played a minor role in recent years in the mission portfolio in the Planetary Science Division (PSD) of NASA's Science Mission Directorate. Indeed, a gap of over 50 years exists between the Stratoscope missions ending in the early 60's and the successful comet and Ceres observations by the BOPPS mission in 2014 where a superheated dust population was discovered on comet C/2014 E2 (Jacques) as reported in Cheng et. al. [1]

While this is notable science, studies (for example [2]) have shown that much more can be accomplished. Work by the Gondola for High-Altitude Planetary Science (GHAPS) project and missions flown by other disciplines have further advanced balloon platform capabilities with improved guiding and pointing technologies, better data return, and the promise of ultra-long and mid-latitude flights. These advances make this platform all the more compelling to investigators as a viable, low-cost, short lead-time, and quick turn-around alternative to space missions.

The extent to which balloon-borne platforms are applicable for planetary science investigations was not fully realized by a broader segment of the planetary community until 2012, when NASA convened a workshop at NASA Glenn Research Center in Cleveland, Ohio to explore what planetary science can be achieved utilizing such a platform. More than 40 science concepts were identified by the workshop attendees and input from the broader planetary science community, and a subsequent science traceability evaluation indicated that *more than 20% of the Decadal Survey "Important Questions" could be answered or significantly addressed using balloon-borne observations.*

The applicability of a balloon-borne platform for planetary science was systematically evaluated in 2016, when NASA convened the Gondola for High Altitude Planetary Science (GHAPS) Science Instrument Definition Team (SIDT), or GHAPS SIDT. GHAPS was intended to be a reusable PSD asset launched on stratospheric balloons with a suite of facility instruments that observers could propose to use for their respective scientific investigations. The SIDT reviewed the current status of the GHAPS optical telescope assembly (OTA), lessons learned from previous planetary science balloon flights, existing instrument technologies, and the decadal survey to define science requirements and present notional instrument concepts that would address multiple decadal-level science questions. Unfortunately, the GHAPS program was canceled in 2017, despite support for balloon-borne investigations from the planetary science community.

Here we demonstrate the continued relevance of balloon-borne observations for addressing fundamental planetary science questions for several classes of solar system targets. A key advantage of a high-altitude balloon platform is access to wavelengths in both the ultraviolet and infrared portions of the electromagnetic spectrum that are inaccessible from ground-based facilities. In this white paper we discuss science opportunities of high-altitude balloon platforms

in the near-infrared where the atmosphere is opaque in the strong absorption bands of water and CO₂, most importantly the 2.5-2.8 micron water band and the 4.2-4.45 micron CO₂ band. These are critically important wavelengths to characterize hydrated species, aqueously altered species, volatiles and ices and can be observed only from high enough altitude or in space. While ultraviolet wavelengths are likewise observable only at high enough altitude or in space, the GHAPS study found that technical requirements for a balloon platform to accomplish both infrared and ultraviolet observations at the same time adds complexity and cost, thus it is recommended that initial efforts be focused on only one of these wavelength ranges. The science cases presented here focus on the NIR-MIR range.

Small Bodies: Balloon-borne platforms are particularly well-suited for the study of small bodies (asteroids, comets, KBOs, etc.) given the ability to observe relatively faint targets (on the order of V magnitude ~20 for a 1-meter class telescope operating near the diffraction limit for exposure times less than 5 minutes [3] without the impediment of telluric absorptions. The 2.5–5 μm region is sensitive to the fundamental vibrational emission/absorption features associated with volatile and organic compounds that can be present on the surfaces of asteroids and comets, such as H₂O, OH, CO₂, CO, hydrocarbons, cyanogens, and absorption features in alteration minerals such as carbonates. Because early impactors are thought to be at least partly responsible for the delivery of volatiles and prebiotic compounds to Earth, understanding the specific volatile and organic mineralogy in the asteroidal and cometary reservoirs would help us understand the origin and evolution of the inner solar system. Such measurements proved especially valuable for the characterization of Vesta and Ceres, which both contain C-type materials on their surfaces with additional materials recently discovered [4], [5], [6]. The spectral features of these condensed phase materials can be well characterized with an instrument with a spectral resolution $R \sim \text{few hundred}$ in the 2.5 to 5 μm range. At 14th visual magnitude, approximately 230 asteroids will regularly be available from a balloon-borne platform.

Characterization of volatiles in cometary comae is another area where balloon-borne measurements can make a significant contribution. Observed activity in comets at large heliocentric distances ($> 3 \text{ AU}$) has traditionally been attributed to species more volatile than H₂O, with CO and/or CO₂ being the most likely candidates. Recent space-based observations from the AKARI satellite, the Deep Impact/DIXI mission, and the Rosetta mission [7], [8], [9] have resulted in a paradigm shift regarding the prominent role of CO₂ among cometary ices. This provides compelling incentive for continued measurements of CO₂ in future comets, which will be limited from JWST due to solar avoidance constraints and the overall demand for astronomical observations. A balloon-borne platform can provide unique studies of CO₂ and potentially the first direct detection and chemical survey of CO₂ from the Earth environment, which is not feasible from ground-based observatories due to telluric absorption.

Venus: One of the fundamental outstanding science questions related to the atmosphere of Venus in which balloon-borne observations can make significant contributions is the cause of its atmospheric superrotation. A balloon-borne platform is ideally suited for investigating Venus' atmospheric circulation. The NIR spectral regime in particular offers a glimpse of several different altitudes throughout Venus' atmosphere due to several atmospheric "windows" that correspond to low-opacity portions of the spectrum, enabling the detection of emission from deeper in the atmosphere. Previous cloud-tracking efforts using IR observations revealed large-scale wind fields, wave phenomena, and variations in the zonal and meridional cloud-top winds on timescales of decades, years, days, and hours. Balloon-borne measurements of cloud motions on Venus can fill an important niche in terms of both temporal and spectral coverage that are inaccessible from

other platforms; NIR images acquired over timescales of minutes to hours can be used to track the motions of Venus' clouds, including both zonal and meridional flows, in an effort to accurately compare observed circulations to model predictions from state-of-the-art Global Circulation Models (GCMs). Although orbiting spacecraft such as Venus Express and Akatsuki provided high resolution NIR imagery of Venus, there was no spectral data. However, it enabled new wind speed measurements [10]. The temporal coverage of the spacecraft data was such that numerous questions remain unanswered (e.g. how is angular momentum transferred throughout Venus's atmosphere? Can we observe Venus's complete Hadley cell-like circulation? What are the drivers for Venus's super-rotating atmosphere?). This will lead to an improved understanding of Venus' global circulation patterns and the processes that control that planet's climate. Because the angular separation between Venus and the Sun is never more than ~ 45 degrees, it is a prime candidate for daytime observations that would be enabled by a balloon-borne platform. A balloon could study SO/SO₂ ratios with UV spectroscopy (not possible from the ground) which, in turn, constrains vertical mixing at the cloud tops.

Lunar Volatiles: The presence of hydrated minerals on the Moon over a wide range of spatial scales has been recognized for at least a decade, but the details concerning the distinction among different volatiles (e.g. OH vs. H₂O), the amount of water present on the Moon's surface, and the temporal variability and migration of this water is still an active area of research. This is an important research area that can be explored by a balloon-borne platform that would be above the terrestrial water vapor. Investigation of phase angle and local time effects on hydration content can probe possible processes controlling the delivery and transport of water at the Moon's surface. NIR spectroscopic observations of the Moon with a resolving power R of ~ 300 at $3\text{ }\mu\text{m}$ and at $6\text{ }\mu\text{m}$, would be valuable to distinguish the phase of observed water, as the chemical state shifts the asymmetric fundamental band wavelength from ~ 2.80 to $2.85\text{ }\mu\text{m}$ in disordered hydroxylated minerals, to $2.95\text{ }\mu\text{m}$ in water (including adsorbed molecular water), and to $3.05\text{ }\mu\text{m}$ for bulk water ice while the $6\text{-}\mu\text{m}$ is only sensitive to the H₂O molecule providing a robust and definitive constraint on identification and H₂O abundance. Spectroscopy of the Moon at $R \sim 300$ also can distinguish H₂O from OH hydration, as this fundamental information is not yet known and conceivably could be spatially or temporally variable, depending on the physical environment in which water-group species are delivered or persist. Infrared imaging with carefully selected narrow-band filters can also make this measurement. From a balloon, individual patches of terrain can be tracked through the lunar cycle from dawn to dusk, to investigate variability. Understanding the distribution, physical state, and variability over time of water (OH, H₂O) on the illuminated Moon is also directly supportive of lunar exploration initiatives.

Giant Planets: Near-infrared images of the atmospheres of the giant planets -- both the gas giants and ice giants -- can enhance our understanding of their coupled chemical and dynamical processes. The infrared regime affords sensitivity to a wide range of altitudes through variations in CH₄ opacity, thus enabling studies of the atmospheric dynamics at depth and their coupling to the uppermost cloud tops. The NIR spectral region includes methane absorption bands at 1.7 and 2.3 microns (in order of increasing strength). These increasingly strong methane absorption bands enable vertical discrimination in the atmospheres of Uranus and Neptune, hence cloud tracking measurements made at these different wavelengths can provide clues into the variation of wind speed with height [11]

The ice giants, Uranus and Neptune, have displayed increased cloud activity over the past decade [12], and the degree to which this is related to seasonal variations in insolation can be explored using high contrast imaging taken at a time cadence that allows complete longitudinal

coverage. The rotational periods of Jupiter, Saturn, Uranus, and Neptune are roughly 9.9, 10.5, 17.2 and 16.1 hours, respectively, hence it is difficult or impossible to observe complete rotations of the giant planets from ground-based or HST observations. Neptune, in particular, is extremely variable on short time scales (days), and better temporal coverage over these timescales is required to understand the energetics and motions of storm development and dissipation. Maximum contrast for Neptune and Uranus is in the methane absorption bands, where the disks of the planets are darker due to methane absorption and the convective clouds and storm features stand out.

This is just a sampling of science that can be achieved, in some cases uniquely, by balloon borne planetary science missions. A wide range of additional solar system targets, including Mercury, Mars, and Centaurs, could also be effectively explored using a balloon borne platform. A balloon-borne observatory may offer some other observational advantages, such as long twilights for targets inside 1 AU. Additional discussion of science achievable can be found in recent literature such as NASA/TM—2016-218870 [2] and the GHAPS SIDT Report [13].

Balloon Platform Capabilities Needed: NASA /TM-2016-218870 describes platform capabilities required to achieve various science objectives. Primary factors that determine the overall capability of a balloon platform to achieve science include: telescope aperture, guidance and pointing precision and stability, instrument performance and observing wavelength range, viewing duration and location (including altitude), and system/environment thermal characteristics.

For a broad range of Infra-Red (IR) investigations, a platform should target observations from targets of brightness greater than 14th magnitude out to 5 μm . At 14th magnitude, hundreds of asteroid, comet and planetary targets will be available for observations, supporting the ability to conduct a broad range of scientifically useful research (see Section 1). And the IR region allows for the study of interesting organic compounds of planetary interest at these targets.

Performance Factors and Today's Capability: Aperture size: The size of the telescope determines the amount of source photons that can be collected and the ability to resolve the source of photon flux. Prior studies, such as those reported in reference [13] and results from the BOPPS 0.8m telescope [1], suggest that a telescope with an aperture size of 1m can achieve much of the science discussed in the previous section. Telescopes of this size for NIR-MIR applications have been manufactured and flown previously on balloon missions so this will not be a technical challenge. For high spatial resolution observations of small scale features on solar system targets, larger apertures may be desired in the future, but within the next decade many investigations can be undertaken with proven balloon telescope capability.

Targeting and Pointing: Ongoing balloon missions in other disciplines are continuing to demonstrate increased performance in targeting and pointing capabilities. In fact, better than 1 arcsec stability is routinely exceeded [1], [14] for many minutes at a time. The Goddard Space Flight Center developed the capability of the Wallops ArcSecond Pointing (WASP) system to deliver sub-arcsecond pointing control, with residual RMS < 0.5". This system is available to future missions, and other pointing systems also exist such as the one used on the planetary BOPPS mission [1]. Pointing requirements scale with wavelength and for IR observations jitter needs to be <0.5", which clearly can be achieved with today's capability as demonstrated, for example on the BOPPS mission where pointing error was significantly less than 0.5" and maintained for over ½ hour.[15]

Instruments and Wavelength: Very capable instruments have been developed for IR observations to support space and sub-orbital platforms. These instruments can not only achieve desired resolutions and processing speed but are also robust enough to fly multiple times with little

rework between flights. This was demonstrated by the BIRC and UVVis instruments which flew in two consecutive years (2014 and 2015) on the BRISSON and BOPPS balloon missions. The desired IR wavelength range discussed here is not only possible but is a unique advantage, as the desired bands are not visible from ground or airborne assets such as SOFIA.

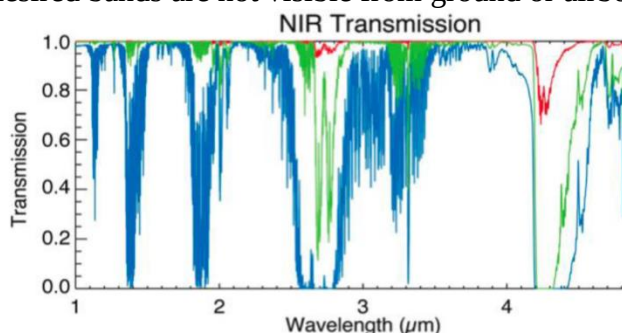


Figure 1. Caption: Atmospheric vertical transmission for altitudes corresponding to Mauna Kea (blue), SOFIA (green), and a balloon at 38 km (127,000 ft) (red) calculated at 1 cm^{-1} resolution for continental summer daytime conditions and a vertical perspective.

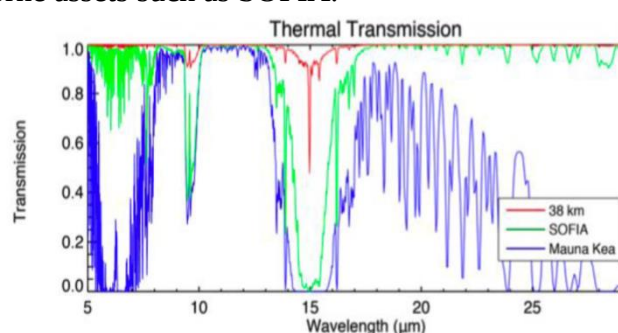


Figure 2. Caption: Thermal infrared atmospheric vertical transmission for altitudes corresponding to Mauna Kea (blue), SOFIA (green), and a balloon at 38 km (127,000 ft) (red) calculated at 1 cm^{-1} resolution for continental summer daytime conditions and a vertical perspective.

Viewing location and duration: Many planetary targets are in the ecliptic plane. To minimize the negative effects of the Earth's atmosphere (e.g. absorption, turbulence, downwelling radiance) observations are best made from low to mid latitude locations. Low to mid latitudes flights also allow for nighttime observations, which are desired or in some cases required. NASA's Balloon Program Office (BPO) routinely launches from facilities that support both acceptable viewing of solar system bodies and nighttime observations.

Because molecules in the Earth's atmosphere can absorb light at wavelengths critical to detection and measurement of desired species, IR observations from the ground are negatively impacted. In fact, for ground-based observations, this effectively makes observations of target water and methane very difficult, and carbon dioxide impossible. In addition, airglow, even at night, can dominate as a main source of noise for IR observations. Thus, higher altitudes enable better science data from the same system, so balloon flights $\geq 30\text{ km}$ are desired both from a downwelling radiance and a telluric absorption perspective (Figures 1 and 2). Referring again to the most recent planetary balloon mission, BOPPS (which weighed over 5,000 lbs) reached altitudes over 38 km, demonstrating that the required altitudes can be achieved even for large telescope payloads with current balloon capabilities.

The BPO is working aggressively toward ultra-long duration flights (100 days or longer). A New Zealand launch facility has been used previously [16] and is being further improved. Mid latitude flights of 100 days would allow for temporal observations supporting a variety of science. For example, volatile elements, with a wide range of sublimation temperatures, are responsible for many of the compositional features in the near-IR. As such, observations of targets at these wavelengths may exhibit variability. The physical processes driving these variations may drive changes on short timescales, on the order of individual observations or longer timescales (diurnal or even seasonal). Investigations of atmospheric dynamics is another obvious class of science temporal measurements would support. Such investigations are not feasible with ground-based

assets nor for time allocation reasons on the flagship Astrophysics observatories Such as the Hubble Space Telescope.

In addition to enabling numerous types of science, long flights, such as a 100-day balloon mission, would enable unparalleled observation time for planetary astronomers at a competitive cost, as shown in the analysis reported in the planetary balloon-based science study [1]. While there is some work still to do to realize ultra-long duration flights, capability exists today for mid-latitude launches from several locations around the globe, some of them allowing flights of several nights or, in the case of Antarctica, many days.

Thermal Requirements: The temperature of the balloon telescope can have a tremendous impact on the sensitivity to infrared wavelengths. If a balloon telescope has a temperature of ~300 K (comparable to ground based systems), thermal self-radiation of the telescope becomes the dominant source of noise at wavelengths longward of 2.2 μm . Lowering the telescope optics temperature to ≤ 250 K will substantially reduce the thermal self-radiation noise, improving sensitivities for science. Techniques have been demonstrated to achieve the needed temperatures using both passive and active approaches such as shades, baffles, precooling, and active thermal management systems [17]. A design will need to be developed for a specific platform, but the technology exists today to address thermal management in the near to mid IR.

Programmatic: Beginning with the 2012 planetary science balloon workshop and subsequently confirmed by the Planetary Balloon-Based Science Platform Evaluation and Program Implementation study, the BRRISON and BOPPS missions, and the GHAPS SIDT report, there is mounting evidence that compelling and cost effective planetary science can be realized from a balloon-borne observatory. Because there is no budget line for planetary suborbital platform development or flights in the PSD budget, the question becomes: How might such a mission be realized? There are a number of approaches both to develop the flight hardware and also for implementing the various missions.

NASA's Astrophysics Division has a suborbital program that competitively funds both the system development and the flights. This approach could be used for planetary science as well.

Another approach, and one favored by the prior planetary science studies, is for NASA to develop an observatory class platform and then compete its use among planetary astronomers. This is similar to the way ground-based observatories are built and used. There are several key advantages to this approach. First, this allows a broader set of scientists to be engaged, since an investigator does not have to be an expert at developing balloon platforms but can focus on the science. A new scientist or science idea can be more competitive since they don't have to compete with a PI that has flown before and has left over and reusable parts on hand. This in effect allows competition to be based more on science merit and less on the financial advantage of having existing hardware on hand. Second, multiple copies of slowing evolving hardware are not funded over and over again, but instead, a single more capable system is available for everyone to use. Third, experts at the hardware and flight execution can develop and fly the hardware, thus lowering risk to a successful flight, increasing science, and lowering life cycle cost. If one follows this approach, the current Solar System Observation program can readily address the competitive selections of the science per mission.

Building the initial observatory would require a direct investment by PSD. Such an investment was used for BOPPS and had been used with the GHAPS project too until it was discontinued to vector resources toward SmallSat activities. This effort can be readily restarted.

The platform can also be built competitively through SIMPLEX, or another mission of opportunity call, but there may be complicating factors of future advantages if the developer also

proposes to the science calls. Whichever approach is used to develop the observatory, it is recommended that the platform be optimized to NIR-MIR observations and science, and not also try to do UV/Vis measurements at the same time. Trying to do both proved to be overly complex for an initial platform development as shown in the GHAPS lessons learned.

From all indications, a balloon-borne observatory promises compelling and cost-effective science for a broad set of planetary astronomers. Such an observatory flying on a regular cadence can be used to engage a broad set of scientists, both early career and seasoned, and return new data from multiple solar system targets. Returned science will support the lunar, small bodies, Venus, and the outer planets communities. Figure 3 illustrates key capabilities and science of balloon-borne missions. Existing ROSES programs can competitively select the science per flight and several approaches are available to build the initial observatory itself.

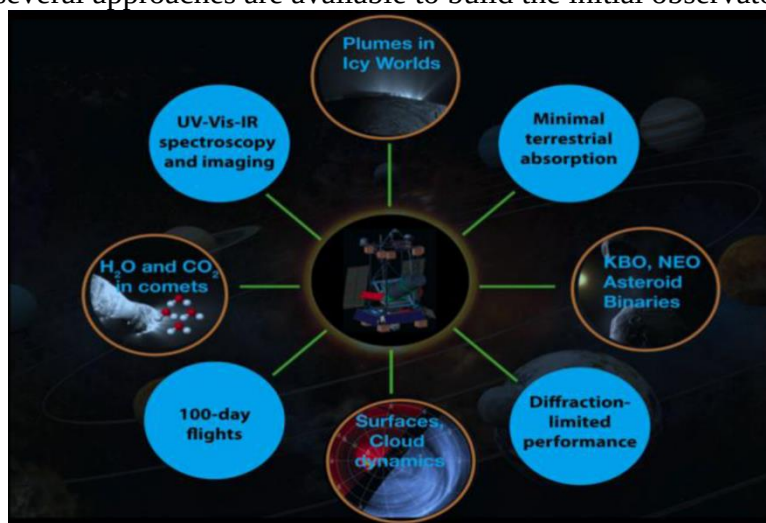


Figure 3 from GHAPS SIDT.
Caption: Schematic showing example science cases that GHAPS can address, along with the principal advantages offered by a balloon-borne observatory for planetary science

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