Balloon-Borne Telescopes for Planetary Science: Imaging and Photometry

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One-Sentence Summary

This white paper advocates the use of balloon-borne telescopes for diffraction-limited imaging in visible wavelengths by demonstrating their technical readiness and low cost relative to space- and ground-based facilities.

Executive Summary

Three of the four divisions in NASA's Science Mission Directorate (SMD) regularly fly large stratospheric balloon missions via NASA's Balloon Program Office (BPO), with Planetary Science being the only exception. Although the Planetary Astronomy Program in ROSES 2008 and 2009 contained a component to support suborbital missions, NASA has funded zero planetary balloon payloads proposals to date.

The purpose of this white paper is to make the case for planetary balloon missions on three fronts: the suite of scientific questions that will be addressed by missions operating in the near-space environment; the cost savings over spacecraft or large ground-based programs that address similar science objectives; and the relative maturity of technologies that would let NASA develop diffraction-limited balloon-borne telescopes.

In astronomy, the most common reasons to seek a space-based platform are (a) high spatial resolution imaging without degradation due to atmospheric turbulence, (b) high contrast imaging with low backgrounds to improve faint-object detection limits, (c) very stable photometry, and (d) detection of radiation that would otherwise be absorbed by the Earth's atmosphere. This white paper advocates balloon missions to accomplish the first three items; the last one (accessibility to the IR spectrum in particular) is addressed in a separate white paper that will be submitted by C. Hibbitts et al.

1. Balloon Capabilities and Costs

This section is a brief overview of NASA's current balloon program (in *FAQ* format).

Q1: What payloads can balloons carry, to what altitudes, and for how long?

NASA's large balloons typically contain about 40 MCF (million cubic feet) of helium and can carry up to four tons of payload to an altitude of 120,000 ft. These are *zero-pressure* balloons, which means that they are open at the bottom. Zero-pressure balloons typically have to dump 10% of their payload (ballast) at night and 10% of their helium during the day to maintain altitude, although Antarctic flights (Dec. - Feb.) are in constant sunlight and can last for weeks.

NASA recently flew a 7 MCF super-pressure balloon for 54 days with less than 500 ft variation in altitude over its entire flight. Because they have no need to dump ballast or helium, super-pressure balloons will enable long duration (~100 days), mid-latitude missions. The BPO plans to test a 22 MCF super-pressure balloon in 2010, with capacity to lift 2200 lbs to 110,000 ft.

Q2: How much does a balloon mission cost?

The cost of a conventional flight (~2 days) from Fort Sumner, NM or Palestine, TX is ~$100K-$250K. The cost of a long duration balloon (LDB) flight (up to 40 days) from Antarctica, Kiruna (Sweden) or Alice Springs (Australia) is ~$250K-$500K. The cost of an ultra-long duration flight (up to 100 days) is ~$500K-$1M (Pierce, 2009). These are deployment costs, separate from payload development.

The payload is recovered and re-usable more than 80% of the time. Also note that the BPO currently flies every payload that is recommended to it by NASA's R&A programs. The bottleneck in Planetary Science payloads lies in the lack of funding opportunities, not the lack of flight opportunities.

Q3: What are the conditions like at 90,000 - 120,000 ft?

Conditions are like space in some regards, critically different in others. At 120 kft, a payload is above 99.5% of the atmosphere, including virtually all of the telluric water vapor and nearly all of the CO_2 and CH_4. The Fried parameter (r_0) is thought to be several meters, implying that a two-meter aperture will provide diffraction-limited imaging. (In contrast, r_0 is about 15 cm at a good terrestrial site). As in space, there is virtually no convective cooling, but unlike the vacuum environment, there is the possibility of arcing if exposed high voltage leads are present. In practice, many balloon payloads fly most of their electronics inside pressurized containers. Nighttime sky brightnesses are similar to those seen by Hubble Space Telescope (HST) in terms of zodiacal light and stellar background, but a stratospheric balloon also sees emission lines, like OH lines. Daytime sky brightnesses are much brighter in the stratosphere but may still allow daytime observations, particularly at long wavelengths and at angles away from the Sun (Fig. 1). Finally, the perturbations to a balloon-borne gondola are generally benign pendulum or twisting modes (Fig. 2). These perturbations are slow, unless the payload itself generates jitter from, for example, momentum wheels or cryo-coolers. The balloon itself acts as a nearly infinite momentum sink, but a balloon-borne telescope needs constant pointing updates to track a target. The pointing problem is perceived to be one of the major obstacles to diffraction-limited balloon-borne imaging, the other being thermal distortion of the OTA (optical tube assembly). Lightweight and/or torque-less telescope designs can can vastly simplify the pointing problem.

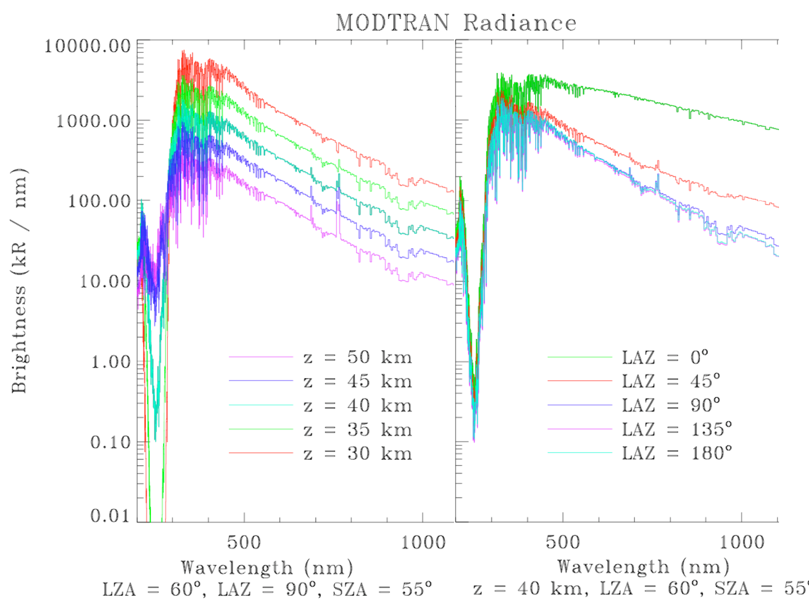

Fig. 1 Two series of MODTRAN simulations to estimate DAYTIME sky brightness as a function of wavelength, altitude and azimuthal angle away from the Sun. In both the left and right panels, the look zenith angle (LZA) is 60° (i.e., an elevation angle of 30°) and the solar zenith angle (SZA) is 55°, just five degrees higher. The LEFT panel looks at sky brightness as a function of wavelength and altitude for a patch of sky that is 90° away from the sun in azimuth. It predicts that the daytime sky brightness increases by 2x for every 5 km decrease in altitude. The RIGHT panel examines sky brightness at different angles from the Sun. Note that there isn't much difference between the sky brightnesses at 90°, 135°, and 180° in azimuthal separation from the Sun. Furthermore, at those particular separations, the sky brightness drops by nearly a factor of seven as the wavelength changes from 500 to 800 nm.

The simulations shown in Fig. 1 reinforce what we already know: that it is bad to look too close to the Sun, that daytime observing in blue or UV wavelengths will have to overcome substantial Rayleigh scattering by stratospheric N_2 molecules, but that near-IR daytime observations may be productive, depending on the brightness of the targets.

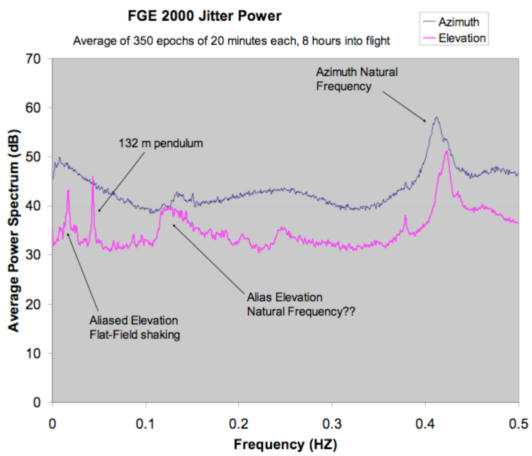

Fig. 2. A power spectrum of mechanical jitter experienced by the Flare Genesis Experiment. It is clear that the major twisting mode, at 0.4 Hz, affects both elevation and azimuth. There is an even slower mode due to the ~300 ft pendulum at 0.05 Hz. Not shown here are higher frequency modes of a few Hz, which are thought to be caused by overtones in the tether and contain very little power. Finally, there may be reaction wheel-rumble at very high frequencies that is not sampled in this plot.

2. The Performance and Promise of Balloon-Borne Telescopes

In a nutshell, the promise of balloon-borne telescopes is to provide *visible-wavelength imaging on par with HST at a fraction of the cost*. We focus on visible wavelengths, not infrared, for two reasons. First, because large ground-based telescopes with AO (adaptive optics) already achieve useful Strehl ratios at wavelengths longer than 1.2 μm (e.g., van Dam et al. (2007) report Strehl ratios of 22%, 41% and 62% in J, H and K bands, respectively, using the Keck II AO system), and second, tenth of an arcsecond performance at 1.2 μm and longer would require at least a 3-m aperture, which is a large payload to carry up to the stratosphere. The real need for diffraction-limited, balloon-borne telescopes is in optical wavelengths, where a simple one-meter telescope could achieve 0.12" resolution. Because of the difficulty AO systems have in correcting atmospheric turbulence at visible wavelengths, a one meter telescope in the stratosphere would outperform every ground-based telescope, every night of the year.

If the comparison between optical balloon-borne telescopes and the HST seems to be technologically far-fetched, consider that (a) balloon-borne optical telescopes are an ancient technology (the 36-inch Stratoscope missions operated in the Earth's stratosphere over forty years ago (e.g., Danielson et al. 1972), and (b) the technology required to stabilize a balloon-borne telescope to 0.1" is essentially COTS (commercial off-the-shelf), as described in § 2.1.

2.1 BALLOON-BORNE TELESCOPES: POINTING & STABILIZATION

There are two parts to stabilizing a balloon-borne telescope: determining pointing errors and correcting them. To take advantage of the seeing conditions in the stratosphere, both of these tasks need to work below the diffraction limit (at ~0.05" for a one meter aperture at visible wavelengths). This is a tall challenge, given the constrained budget of most balloon payloads, but not an insurmountable one. A reasonable strategy is to use a star tracker to get coarse pointing information and a quad-cell array for fine pointing at high frequencies. For tracking on a target, many balloons currently use two stages: coarse telescope tracking and a fine steering mirror.

2.1.1 *MULTISTAGE DETERMINATION OF POINTING ERRORS*

The Star Tracker 5000 (ST5000) is an inexpensive star tracker that has been proven on several recent sounding rocket flights. Cost per unit is around $100K. The ST5000 determines a lost-in-space solution in about 10 - 30 seconds, and updates its pointing information at a 10 Hz rate. The rms pointing solution from the ST5000 is about 0.5” in yaw and pitch (somewhat higher in roll). Since 0.5” is an order of magnitude too coarse for maintaining diffraction-limited performance, it is likely that a balloon-borne telescope will have an additional sensor to determine very small perturbations at high frame rates. This sensor could be digital (e.g., a fast CCD typically used for wavefront sensing in AO systems) or analog (a photodiode quad cell), but it will most likely cohabitate the focal plane alongside the science detector.

Fig. 3. The ST5000 head unit, including optics and CCD detector.

2.1.2 *MULTISTAGE POINTING STRATEGIES*

Many balloon payloads have implemented pointing systems that keep their telescope (or other payload components) oriented to within a few degrees of the intended target. The amplitude of the tether twisting mode can be tens of degrees in azimuth (although typically with a period that is close to a minute), so the telescope pointing system will be exercised continuously. A video taken during previous NASA balloon flights is available on the lower left corner of the High Altitude Student Payload web page (<http://laspace.lsu.edu/HASP/>, the *CosmoCam* flight video). This footage shows that gondola perturbations are very slow-moving once the balloon reaches float altitude.

The perceived difficulty in achieving accurate pointing is bridging the gap between a few degrees and 0.05 arcseconds. Many scientists are surprised to discover that COTS fine steering mirrors routinely span ranges of a few degrees, but achieve precisions of nanoradians (0.05” is about 240 nanoradians). The fine steering mirror shown in Fig. 4 is less than $100K with its associated electronics. Given an accurate pointing error signal, it can correct errors from tens of nanoradians to a few degrees at rates of several hundred Hz.

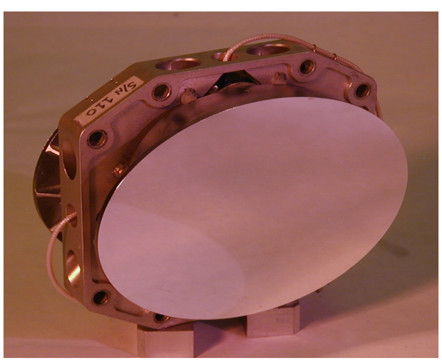

Fig. 4. A Fine Steering Mirror from Left Hand Design in Longmont, CO.

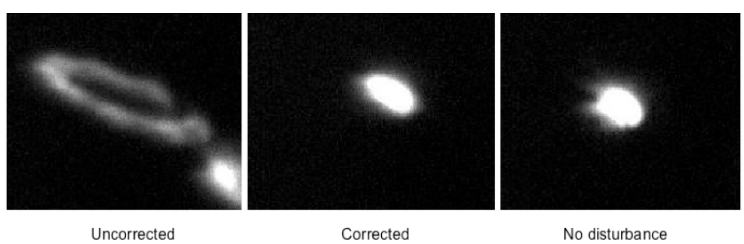

Fig. 5. Results from an experiment with a telescope equipped with a fine steering mirror (Fig. 4) in place of its usual diagonal mirror. *LEFT*: a star from the shaken scene generator. *MIDDLE*: The same star after the fine steering mirror was turned on, using an error signal from a bright star fed to a lateral effect cell. *RIGHT*: The unperturbed star. (Kraut et al. 2008.)

2.1.3 *NO FINE POINTING: FREEZING THE IMAGES*

While stabilization is often cited as the leading technological challenge facing balloon-borne telescopes, the problem can be sidestepped completely by “freezing the motion” with rapid short exposures and co-registering them in a post-processing pipeline. It is a cheaper, simpler option, than a telescope stabilized at the diffraction limit. It does require a detector that is capable of short exposures, little or no dead-time, and extremely low read noise.

EMCCDs (Electron-Multiplication Charge Coupled Devices) achieve low read noise by applying a gain factor to charge as it is read out of an extended serial register. Even though there is noise associated with the read-out electronics, the effective read noise can be less than an electron per read when the signal is normalized by the gain factor. The down-side of EMCCDs is that other noise sources (photon shot noise associated with the source, background and dark current) is multiplied by the serial register too, by about 40% (Robbins 2003). Exposure times must be doubled to compensate for that effect.

2.2 BALLOON-BORNE TELESCOPES: PROSPECTS FOR PHOTOMETRY

With less than 0.5% of the atmosphere overhead, a telescope at 120,000 ft can perform extraordinarily stable photometry. Table 1 compares the expected SNR (signal-to-noise ratios) for a 1-m stratospheric telescope and the Hubble Space Telescope. The HST has several advantages over the 1-m telescope, such as a narrower PSF (so less background is integrated with the object), lower background (both telescopes see the same zodiacal and stellar backgrounds, but the 1-m also sees variable sky lines in emission), and the HST’s aperture is equivalent to a factor of 4 in exposure times.

However, the differences between HST and a 1-m stratospheric telescope are small compared to the advantages that the 1-m telescope has over ground-based installations. At visible wavelengths, even telescopes equipped with AO or tip-tilt correction will have PSFs that are generally 2x - 3x wider than that from a 1-m balloon-borne telescope. The stratospheric telescope is above virtually all telluric water, there’s no need to model extinction vs. airmass, and there is no variable cloud cover. In addition, the stratospheric telescope needs no guide star, whereas the Keck AO system needs a V=17.5 star or brighter within 50’ of the target, even when using laser guide star AO.

Vmag	T (s) SNR=100 (EMCCD)	T (s) SNR=100 (FSM)
15	3.1	1.6
16	7.8	3.9
17	19.8	9.9
18	50.0	25.0
19	128.8	64.4
20	342.1	171.1
21	981.5	490.8
22	3,210.5	1605.3
23	12,723	6361.5

Table. 1. SNR predictions (seconds required for a SNR of 100) for a 1-m telescope in the stratosphere for a fast-exposure strategy (EMCCD) or a fine steering mirror approach (FSM). Read noise is assumed to be 3 e-/read for the FSM case. A CCD with quantum efficiency of 90% is assumed.

How do the predicted exposure times for a 1-m telescope compare to HST’s performance? In HST/HRC discovery images of Pluto’s satellites Nix and Hydra, the satellites were detected with SNR ≥ 35 from two 475 s exposures (Weaver et al. 2007). Assume Hydra (V=23) had an SNR of ~50 in 950 seconds, then the HRC should achieve a SNR of 100 in about 3800 s, compared to 6361 s predicted for the 1-m telescope.

Unlike HST, however, a balloon-borne telescope can track an ecliptic solar system object for longer than 50 minutes and should be able to slew from object to object with a more efficient duty cycle than HST.

3 Planetary Science from Balloons: Some Scientific Applications

This white paper cannot cover all the science applications that would benefit from an imaging system with high-spatial resolution and low background. Here we give a few examples of types of observations that would benefit from long-term access to 0.1" imaging in visible wavelengths.

- *Long-term monitoring of the atmospheres of gas giants and ice giants in visible wavelengths.* Currently can only be done with HST. Visible wavelengths probe different depths than J, H and K wavelengths from ground-based observatories with AO capabilities. Unlike HST, which allocates a few visits per year on Neptune or Uranus, a balloon mission could take several weeks of continuous observations to dramatically change our understanding of the evolving weather patterns on the ice giants. The visible wavelengths sound different depths than the J, H and K bands imaged by ground-based AO facilities.

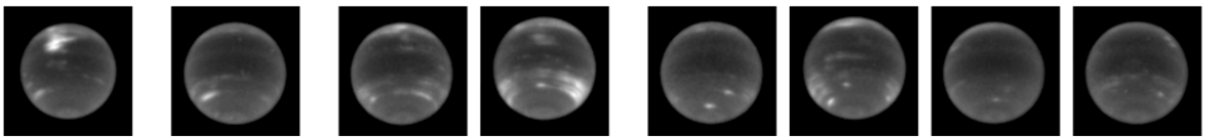

Fig. 6 Neptune in the 0.619 μm filter of HST/WFPC2 in 1994, 1997, 2001-2002 and 2004-2007 (L to R).

- *Detection and characterization of asteroid and TNO binaries*. The distribution and characteristics of binaries is a powerful constraint on their putative formation mechanisms[1]. A large sample will need to be observed in order to draw meaningful conclusions about the prevalence of distinct formation scenarios. A dedicated balloon mission is well-suited to searching for asteroid and TNO binaries: balloon-borne telescopes have the spatial resolution and contrast to detect faint objects next to brighter objects and the photometry to detect shallow rotational lightcurves. HST and ground-based AO facilities (like Keck) have been used for this purpose, but those facilities are drastically overcommitted and cannot allocate the time necessary for this kind of project.
- *Searches for faint NEOs (near earth objects)*. A wide-field 1-m telescope that can be flown (and re-flown) on a long-duration stratospheric balloon would have a detection limit that is significantly better than those of current ground-based NEO surveys. In addition, the 1-m telescope would produce superior astrometry (and orbit estimates) of discovered NEOs and therefore provide a longer window for follow-up detections. Balloons can be deployed over most latitudes to fill gaps in ground-based programs that cannot easily access all declinations.

4 Cost-Effectiveness of Balloon-Borne Platforms

Balloon-borne telescopes have unique imaging capabilities in visible wavelengths, matched only by HST, but how much would do balloon observations cost on a night-by-night basis? NASA generally funds balloon payloads through the APRA Research and Analysis program. A typical

[1]Putative binary asteroid formation scenarios include (a) Smashed Target Satellites, in which some ejecta from a non-catastrophic impact accretes into a satellite, (b) Escaping Ejecta Binaries, in which a parent body is disrupted and some of the escaping fragments follow similar trajectories and eventually form a gravitationally bound pair, (c) Fission satellites from an asteroid that is spun up by collisions until centripetal accelerations are stronger than the object's internal self-gravity, and (d)YORP satellites, in which the parent asteroid is spun up by the absorption and re-radiation of photons. These scenarios are thought to produce distinct and observably different ensembles of binary asteroids (Durda et al. 2004).

payload might cost between $3M - $10M, including salaries, gondola telescope, OTA, detector, electronics for data control and handling, among other things. Some of these payloads are significantly more complicated and expensive than a 1-m visible wavelength telescope, especially their detectors: commercial frame-transfer EMCCDs are a relatively inexpensive $20K - $35K.

A simple gondola with a 1-m gregorian telescope, coarse pointing (gimbals) capable of tracking a target to within 5”, an EMCCD detector, with moderate lightweighting of the primary mirror, is roughly a $600K - $800K package. The addition of a star tracker, a fine pointing sensor, and a fine steering mirror adds around $400K - $500K to the cost of the payload. The deployment costs for a long duration flight (up to 40 days) is $250K - $500K, according to Pierce (2008). Taken together, the cost per night ranges from $31K to $45K. The cost per observation is even less if (a) the payload can be used for daytime targets (e.g., Uranus and Neptune) and (b) the payload can be re-flown on subsequent flights for a fraction of the initial development costs; two 40-day flights of 24-hr observations reduces the balloon rate to $7.7K - $11.2K per twelve-hour period.

How do these costs compare with spacecraft or ground-based telescope costs? The cost per night on Keck is well known, thanks to their participation in the NSF’s TSIP program, where instrument development costs are partially repaid by a contribution in public (but competed) observing nights (http://www.noao.edu/system/tsip/keck-cost.php). The nightly cost on Keck in FY03 was $47.4K per night, based on amortized telescope and instrument development costs plus annual operations costs. It is cheaper (per night) to build and deploy a diffraction-limited 1-m telescope to the stratosphere on long duration super-pressure balloons than to build and operate a 10-m telescope on Mauna Kea with sophisticated AO capabilities.

NASA’s least expensive spacecraft are built under the SMEX (Small Explorer) program. If payload development is assumed to cost ~$100M for a two-year mission, the cost per twelve-hour period is $68.5K (ignoring launch costs). While spacecraft should obtain science results that cannot be quantified as nightly rates, it is clear that a balloon deployment to *near* space is dramatically less than even a SMEX spacecraft deployment.

5 Conclusions

- Balloon missions will last many tens of days using long-duration super-pressure balloons.
- The technology required to point and stabilize a telescope at the 0.05” level is not especially exotic nor expensive.
- There are many planetary science projects that could take advantage of 0.1” resolution in visible wavelengths.
- A 1-m diffraction-limited balloon-borne telescope is significantly cheaper (per night) than the Keck telescope and is dramatically cheaper than a strawman SMEX mission.

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