EXECUTIVE SUMMARY:
A ROADMAP FOR SCIENTIFIC BALLOONING 2020-2030

Report of the NASA Balloon Program Analysis Group

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1 INTRODUCTION

The exploration of the Earth, the stratosphere, the solar system, and the cosmos beyond it from balloon-borne scientific instruments has a long and lustrous history. Scientific ballooning has progressed in a continuous arc from early beginnings in the late 18th century when the first measurements of air temperature vs. altitude were made from a balloon payload, to our current era where almost every branch of astrophysics, space science, Earth science, and planetary science garner contributions from balloon missions. There is every reason to believe that this rate of scientific productivity will continue its remarkable trajectory into and beyond the next decade.

Our goals in this report are to distill the scientific context and directions from a diverse and creative community of investigators, educators, and technologists, in a way that will help to prepare us to meet the scientific needs of both the next decade, and a new generation of investigators who are even now engendering new avenues of research. Scientific ballooning has over the years acquired another important role within NASA's broad portfolio of missions: that of a critical training ground for students and early-career investigators at many different levels. This is due both to the relatively short duration of the projects, which is well-matched to the several-year tenure of both students and researchers, and to the low relative costs of balloon payload and the associated missions, which enables greater participation of students and early career scientists in project roles that would otherwise be reserved for far more senior personnel. In all of the PAG assessments presented here, we maintain a goal of preserving such access.

In the following sections, we briefly identify high priority scientific drivers in all of the major disciplines relevant to the NASA balloon program, including Astrophysics, Earth Science, Planetary Science, Solar & Heliophysics, Education & Public Outreach, and Balloon program technologies. The PAG does not here advocate for specific payloads, but rather has selected those science drivers across many disciplines that rely on scientific balloons, and that we find are of the most compelling significance for the next decade. After describing these, we conclude with a set of findings and recommendations to the NASA Balloon Program in response to these scientific priorities. We refer the Astro 2020 panel also to an online version of both our draft report, along with a collection of documents from community input that were used in the process, referenced here.[1]

2 ASTROPHYSICS

Within the Astrophysics discipline, balloon-borne payloads are used in a diverse set of fields, involving diffraction-limited telescopes, particle detectors, and even compact radio interferometers. In this section we summarize these fields and highlight our perceived priorities within them.

2.1 Astroparticle Physics. The study of atomic and subatomic-scale particles of cosmic origin is a discipline requiring large collecting areas to overcome the very low fluxes, via both direct measurements using particle tracking detector, and indirect measurements using secondary emission from ultra-high energy (UHE) particle cascades in large natural targets such as Earth's atmosphere or Antarctic ice, observed from the radio to the visible spectrum. Balloon payloads have and will continue to play a critical role in this area through the next decade.

Cosmic Ray composition and spectrum below the knee. The composition of cosmic rays in the TeV to PeV energy range provides unique visibility into important high-energy astrophysics processes in the galaxy and interstellar medium. Balloon payloads still play a critical role in the exploration of particles in this energy regime, since they are able to deliver large mass, large area to altitudes high enough for primary composition measurements at low cost.

Cosmic Antiparticles. At tens to hundreds of GeV, cosmic antiparticles are observed by both spacecraft and balloon-borne payloads. The spectral energy distribution of positrons and antiprotons may indicate the presence of nearby pulsars in the solar neighborhood, but may also arise from dark matter decay scenarios. Detection of certain particle species, such as anti-helium nuclei or anti-deuterons, could provide

compelling evidence for particle dark matter.

Ultra-high energy cosmic rays & neutrinos. The mystery of the sources of the highest energy cosmic rays, at Exavolt (10^{18} eV) to Zetavolt (10^{20} eV) energies, remains a compelling question in the field of particle astrophysics. Detectors using Antarctic ice have now begun to open a new observing window for neutrinos in this area,[2] and balloon payload sensitivities to EeV neutrinos have grown steadily, providing important and unique astrophysical constraints,[3] and possible evidence of unexpected signals.[4] Balloon-borne payloads have a unique physics reach in the ultra-high energy range, with float altitudes above Antarctica providing a very large observable target volume, but at a proximity not available from space, thus giving an important advantage in a low particle energy threshold to events arising from particle interactions near the Earth's surface.

2.2 Exoplanets & Stellar Astrophysics. High altitude balloons, especially long-duration balloons, are real alternatives for large satellite missions. They demonstrate cutting-edge technologies, are recovered, refurbished and reused to address important scientific questions. In certain disciplines, they have been targeted as the ideal platform for moving the field forward. Exoplanetary studies is one example of such usage.

Exozodiacal dust. Balloon payloads are an excellent platform for the study of exozodiacal debris. The bright zodiacal light in our solar system is produced by the scattering of sunlight off 1-200 μm dust grains that are continually replenished by outgassing comets and colliding asteroids. Exozodiacal dust is the dominant astrophysical background that needs to be characterized and quantified in order to successfully image exoplanets. Furthermore, coronagraphic studies of debris disk morphology are important in answering fundamental questions such as how circumstellar disks evolve and form planetary systems. These structures are accessible to balloon-borne measurements employing meter-class telescopes, and as these debris discs are relatively bright, observations can be made in daylight.

Exoplanetary transit observations. The phase curve of an exoplanet describes changes of its brightness during an orbital period. Spectroscopic observations of exoplanetary transits can be used to determine the inhomogeneous chemical composition and cloud coverage of the planet. The value of spectroscopic observations of phase curves for transiting planets to determine their atmospheric composition, thermal structure and dynamics of exoplanets has been demonstrated with both ground and space-based observations.

However, further progress requires precision spectroscopic observations of complete phase curves which are very difficult to obtain without continuous observations. Such spectroscopic phase curves could be obtained during an entire orbital period from long-duration balloons for short period transiting planets; such measurements are not possible from Low Earth Orbit (LEO) satellite platforms due to orbital and scheduling constraints.

Stellar Astrophysics. The major impediment to high precision IR photometry is water vapor; thus stratospheric balloons, which float above the tropopause and its associated cold trap, are the ideal platform for near to mid infrared photometric measurements. Specifically, high precision photometric measurements, currently of limited precision for the $\sim 10,000$ brightest stars due to saturation in high sensitivity modern surveys, are needed to complement the very high resolution space and ground based measurements, which are necessarily of limited sensitivity, used to compare with physics-based models of exoplanet atmospheres, cool stars, and evolved stars. These photometric measurements can easily be obtained from a high altitude balloon.

Terahertz astrophysics. The TeraHertz (THz) portion of the electromagnetic spectrum (1-10 THz) provides us with a powerful window into cosmic evolution. THz photons arriving at Earth provide valuable insights into everything from the birth and death of stars to the cataclysmic events associated with the origin of galaxies and the Universe itself. Many of the THz photons we observe are emitted by the gas and dust be-

tween the stars, that is, the interstellar medium (ISM). At THz frequencies we can observe photons associated with the ISM of our own galaxy, the Milky Way, as well as from the ISMs of distant galaxies. Today the ISM accounts for only 1% of the total gravitational mass of the Milky Way, with the balance being in stars (9%) and dark matter (90%). However, in the beginning, most of the Galaxy's baryonic mass was in ISM. It was, and continues to be, the mass and energetics of the ISM that is a principal driver of galactic evolution.

The evolution of THz astronomy has been driven largely by two factors; 1) atmospheric absorption of THz light and 2) the availability of detector technology. Water vapor in the Earth's atmosphere is a very efficient absorber of THz photons Therefore, THz observations are best conducted from high altitude balloon-borne telescopes or space-based telescopes. Utilizing recent breakthroughs in detector technologies, such observatories have or will serve as powerful probes of the life cycle of the ISM, both in our own Milky Way and beyond. Due to their ability to take heavy payloads to the edge of space, high altitude balloons allow the possibility of realizing large aperture telescopes (> 5 meters) with sophisticated cryogenic instruments at a fraction of the cost and time associated with achieving similar capabilities on an orbital mission. With such observatories it will be possible to probe the intricacies of star and planet formation, as well as the origins of galaxies.

2.3 High Energy Astrophysics. High energy astrophysics is the study of the extreme Universe. The x-ray and gamma-ray sky shines with non-thermal emission from high-energy environments, such as jets, AGN, black holes, GRBs, and x-ray binaries. Balloon-borne measurements in this energy range require high altitudes to reduce atmospheric absorption, and long exposure times to account for the high atmospheric backgrounds and low source fluxes.

MeV Astrophysics. Technology advancement is key in this relatively unexplored energy range. The MeV sky was first opened by CGRO/COMPTEL in the 1990s,[6] but many interesting science topics remain, from gamma-ray line measurements of Galactic nucleosynthesis and positrons annihilation to continuum studies of high energy events and sources such as pulsars, high red-shift blazers, and GRBs.[7,8] Not only has the balloon platform enabled the necessary technology development in this challenging energy range over the past decade, but with the realization of NASA's new Super Pressure balloon, ultra-long duration flights will soon allow for sufficient exposure to accomplish competitive science goals at the relative low cost of a balloon mission. Additionally, the newly available southern hemisphere launch location in Wanaka, New Zealand, allows for exposure of the Galactic Center region, which is an important MeV science target, especially for studies of positron annihilation.

Hard x-ray and gamma-ray polarization measurements. Polarization measurements in the hard x-ray and gamma-ray regime are just beginning to be realized, and balloon-borne instruments are at the forefront of this novel technique.[9–11] These measurements give unique insight into high energy phenomena with a diagnostic of the emission mechanisms and source geometries for GRBs, galactic black holes, AGN and accreting pulsars. Recent measurements of hard x-ray and gamma-ray polarization from balloon-borne instruments have demonstrated this technology,[12] and the timing is optimal to complement the upcoming IXPE satellite mission, which will perform polarization measurements at lower energies. Long duration balloon flights are generally required for high-energy polarization measurements to allow for sufficient exposure of these sources and at the same time give a higher probability of catching a flaring or transient source. The Wallops Arc Second Pointer (WASP) has enabled much of this science in the hard x-ray regime.

2.4 Observational Cosmology.

2.4.1 The Cosmic Microwave Background. In the post-Planck era, and in anticipation of the ambitious next generation of ground-based CMB projects, the scientific ballooning platform represents a unique and enabling scientific opportunity. Broadly speaking, the measurements enabled fall in two classes. At frequencies

above 220 GHz, near the peak of the CMB signal and where Galactic polarized dust emission dominates, the advantages of the stratospheric platform over the best terrestrial sites are overwhelming. The lack of atmospheric contamination and the ability to cover a significant fraction of the full sky allows balloon borne instrumentation access to the largest angular scales, which are of critical importance both for characterizing the epoch of reionization and for probes of primordial gravitational waves.

2.4.2 Cosmic Concordance. Cosmological observations at high- and low-redshift , including measurements of the Hubble parameter and of the large scale distribution of matter, provide independent tests of the standard cosmological model. The unique capabilities of the Hubble Space Telescope have proven invaluable in the development of this field. Long-duration mid-latitude Super Pressure Balloon flights offer tantalizing opportunities for expanding well beyond the capabilities of HST from the near-UV to near-IR wavelengths, offering space-quality diffraction limited wide-field imaging and spectroscopy. The relatively rapid development cycle of the balloon payloads is well poised to take advantage of the exponential growth in the imaging technology that is transforming the field. Importantly, these capabilities will not be provided in the coming generation of large missions, including JWST and WFIRST.

3 Earth Science

The climate structure of the Earth is undergoing rapid and unprecedented changes. These changes have global impacts, demanding critically needed studies and forecasts of: (1) hurricane formation, intensity and trajectory, (2) the rate of sea level rise, (3) climate-forced changes in the large-scale dynamics of the atmosphere, (4) wildfire risk, (5) shortwave forcing of the climate that is the dominant uncertainty in climate forecasts, (6) drought and agricultural production, (7) severe storm initiation, development and geographic coverage, (8) Arctic sea and glacial ice breakup, (9) UV radiation increases over the central United States in summer, (10) risk of flooding, (11) increases in CO_2 and CH_4 emission globally, and (12) cirrus cloud, pyrocumulus, and volcanic eruptions impact on climate.

3.1 Response of Large Scale Atmospheric Dynamics to Carbon Dioxide and Methane.

As greenhouse gases increase in Earth's atmosphere, the stratosphere is predicted to have two distinct responses. First, as the surface warms, the stratosphere cools, and both observations and models show that stratospheric cooling is a robust response to increasing radiative forcing by greenhouse gases. Second, chemistry-climate models universally predict that the Brewer-Dobson circulation (BDC), the primary circulation pattern in the stratosphere, should be accelerating in response to greenhouse gas increases. The BDC is responsible for transporting trace gases, such as water vapor and ozone, that are critical for radiative forcing and impact surface weather and climate. The acceleration of the BDC predicted by models would be a positive feedback on the increased radiative forcing by greenhouse gases. However, rates and patterns of the BDC inferred from observations are not consistent with each other or with model predictions, raising important questions.

A balloon-borne stratospheric Earth-observing payload can systematically and comprehensively map the details of this dynamical structure globally employing an array of high spatial resolution in situ measurements of short, medium and long-lived atmospheric tracers in combination with highly sensitive dynamical observations of three-dimensional velocity fields, wave-breaking structures, momentum transport and heat transport as well as radiance divergence observations. These are the detailed, high spatial resolution observations that are critically needed to quantitatively establish the dynamical structure of the atmosphere required to develop tested and trusted forecast models of climate response to rapidly increased forcing by carbon dioxide and methane.

3.2 Terrestrial Gamma-ray Flashes (TGF).

Intense sub-millisecond bursts of energetic photons in excess of tens of MeV have been observed from terrestrial sources by satellites for 25 years. These Terrestrial Gamma-ray

Flashes are localized in regions of high thunderstorm activity and are thought to be caused by bremsstrahlung of electrons in the atmosphere accelerated by the high electric fields in thunderstorms and associated lightning. Recent ground experiments have been able to correlate TGF events with local lightning events, but the details of the gamma-ray generation mechanism and the relationship between ground and satellite observations remain uncertain. Balloon payloads, possibly hand launched, would be capable of traveling over thunderstorms, intercepting the upward beam of TGF gammas providing a link between local and satellite observations and new constraints on gamma-ray burst generation models.

4 Planetary Science

At the time of this writing NASA has no proposal opportunities that could fund balloon missions in planetary science. This obstacle is specific to the Planetary Science Division among the four divisions within the Science Mission Directorate. It does not mean that planetary scientists could not benefit from balloon missions – on the contrary, the recent GHAPS/SIDT report (Gondola for High Altitude Planetary Science/Science Instrument Definition Team) outlines many planetary investigations in which a balloon mission would yield low-hanging fruit. Of the roughly 200 important questions listed in the at least 44 that are clearly addressable from balloon platforms, generally because of access to key wavelengths or diffraction-limited imaging at UV and visible wavelengths, where ground-based adaptive optics (AO) systems have poor Strehl ratios.

The atmospheric windows for observation beyond the visible-light bands are crucial to planetary science in the near-infrared and thermal infrared, as well as the near-ultra-violet. Here we show a comparison of transmission curves for three altitudes, including balloon-borne systems.

4.1 Atmospheric Dynamics. The gas giants (Jupiter and Saturn), the ice giants (Uranus and Neptune), Mars, Titan and Venus all have observable clouds that can be tracked to study atmospheric dynamics. There is a rich history of dynamical studies on these objects [Refs], either from spacecraft or from high-acuity assets like Keck/AO or HST (Hubble Space Telescope). Because different wavelengths sound different altitudes, it has been useful to combine HST imaging (at $\lambda = 0.2 - 1\mu$m) with ground-based adaptive optics (typically $\lambda = 1 - 2.5\mu$m). One problem has been the availability of observing time: the total number of days available on Keck or HS may be less than the number of days needed for an investigation (e.g., weeks of cloud tracking to characterize planetary scale waves or other long-lived phenomena).

Tracking Venus's cloud tops at UV wavelengths. The two most recent missions to Venus, VEx (Venus Express) and Akatsuki, were both equipped with UV cameras to image Venus at 283 (sensing SO_2) and 365 nm (the unknown UV absorbers). Both missions could image Venus's full disk at these wavelengths with spatial resolutions of about 20 km, although VEx's eccentric polar orbit only obtained full-disk images of Venus's southern hemisphere and Akatsuki's eccentric equatorial orbit provides irregular sampling with coarser resolutions over most of its orbit.

A balloon-borne terrestrial 1-m aperture telescope has a diffraction-limited resolution of 75 mas at 365 nm, commensurate with a spatial resolution of 30 km on Venus from a distance of 0.55 AU. Larger apertures could actually exceed the spacecrafts' resolutions. A Venus balloon mission could carry additional UV filters (e.g., with sensitivity to both SO_2 and SO), and, unlike the spacecraft missions, it could obtain images at 10-min intervals over up to a 100-day baseline to help characterize Hadley cell-like circulation, convection, gravity waves (some launched by Venus's mountains) and planetary scale waves.

Tracking Venus's lower and middle cloud decks. Venus's CO_2 atmosphere has transmission windows at 1.74 μm and 2.2 - 2.6 μm, where thermal emission from the hot surface and lowest scale heights of the atmosphere show reveal clouds from 48 - 55 km as silhouettes. Cloud tracking in these wavelength windows determines wind fields that constrain Venus's circulation, and the distribution of cloud opacities, particle sizes and chemical composition constrain

the coupled radiative-convective-chemical processes that control Venus's atmosphere. At 1.74 and 2.3 μm, the diffraction limit of a 1-m aperture is 440 and 580 mas, respectively – hardly better than good ground-based sites. Image sequences from the IRTF can resolve cloud motions with errors at the 3 m/s level in good seeing conditions, but the goal should be 0.5 m/s errors, in order to resolve meridional winds that are expected to be $\sim$1 m/s. A large aperture – about 3-m in diameter – and a 6-hr observing interval are necessary to achieve the 0.5 m/s goal.

4.2 Comets. *Comets in UV and IR Wavelengths.* The composition of cometary jets can help determine where a comet formed in the early solar nebula, based on the idea that different volatiles condensed at different distances from the Sun. Two wavelengths are particularly useful: OH lines at 308 - 311 nm, which serve as a proxy for water production, and the CO_2 band at 4.3 μm. The former can be observed from the ground, but with telluric extinctions around 50%; the latter cannot.

Cooled OTAs for IR Wavelengths. Heat transfer in the stratosphere is dominated by radiative and conductive processes. There is an advantage to reducing the thermal emission from the telescope optics and the OTA enclosure: on the BOPPS mission, thermal emission from the primary and secondary mirrors accounted for approximately two-thirds of the background counts at 4.3 μm, despite the fact that the primary mirror was coated with low-emissivity gold. We recommend studies on ways to cool the OTA, beginning with sun- and earth-shields. Preliminary thermal models suggest that passive shielding can reduce the daytime temperature of a telescope by 100 K, which translates to nearly a factor of 6x reduction in thermal background from a telescope's own mirrors.

4.3 Asteroids and Trans-Neptunian Object Satellites. *Satellite detections.* Satellite detections and their orbit characterizations can potentially (a) determine the mass of the central body, (b) constrain formation scenarios and (c) rule out classes of events (e.g., impacts, close encounters) in an object's history. These detections can be challenging, since they often entail identifications of faint objects adjacent to bright objects. This means that the PSF halo is of paramount importance. Cloud tracking (or other imaging of low-contrast fields) is relatively tolerant of power in a PSF's halo, as long as the PSF's core is narrow. Satellite detection require low power in the PSF halo to ensure that the satellite is not swamped by light from the central body. The best wavelength region (in terms of the best SNR) is often in visible wavelengths because of the peak in solar flux, but can be in specific absorption bands if the central object is covered in certain constituents (e.g., water ice).

5 HELIOPHYSICS

Balloon experiments have a rich history in both solar and magnetospheric physics, with significant contributions in science areas ranging from solar flares to particle precipitation into Earth's upper atmosphere to measurements of large-scale magnetospheric electric fields. In addition to producing important stand-alone science, these experiments have worked in tandem with larger NASA missions to augment their science return and have contributed significantly to the development of Explorer-class satellite missions.

5.1 Solar Physics. Balloons can carry large and powerful optical telescopes high above the atmosphere where they make ultra high-resolution observations of the Sun at 50 km spatial scales, 3x better than the state-of-the-art Hinode space mission.[13] Balloon-borne experiments also make measurements at UV wavelengths that are unreachable from the ground due to atmospheric absorption.

Gamma-ray observations of the Sun require heavy instruments, making balloons an ideal platform. Gamma-ray imaging indicates that solar flares accelerate and transport ions differently from electrons. The angular resolution of the current state-of-the-art balloon experiment is significantly better than any spacecraft observatory to date (e.g., RHESSI). Long-duration balloon flights are critical for catching infrequent transient events such as solar flares. Recommendations for solar physics.

5.2 Particle Precipitation into Earth's atmosphere. Particles with energies spanning more

than four decades - from auroral electrons (100 eV - 10 keV) to relativistic electrons from the Van Allen belts (100 keV - MeV) - rain down onto Earth's upper atmosphere from space. Auroral precipitation controls the nighttime conductivity of the ionosphere while relativistic precipitation plays an important role in the dynamics of the Van Allen radiation belts and may also be important for the creation of HOx and NOx that destroy ozone. Electron microburst precipitation was discovered with balloons[14] and is known to be an important loss mechanism for the radiation belts. These rapid bursts of precipitation provide an ideal target for studying the physics of non-linear wave-particle interactions in space plasmas. Balloons can easily distinguish the spatial and temporal variations of these bursts which is difficult from a LEO satellite. Experiments are under development to perform high-resolution imaging of relativistic electron precipitation, only possible from a balloon platform. These measurements will, for the first time, quantify the distribution of microbursts scale-size, revealing important information about the connection with plasma wave spatial scales near the equator.

5.3 Thermospheric Winds. Joule heating in the high latitude regions of Earth has an important impact on the global circulation of the thermosphere, a part of Earth's upper atmosphere. The magnetosphere, driven by the solar wind, is now understood to be an important source of energy input to the thermosphere. However, the details of the energy transfer process are not well-quantified, and the effects of geomagnetic activity, season, and geomagnetic latitude are not well-studied. Balloon-borne experiments can monitor thermospheric neutral winds by measuring the Doppler-shift in airglow emissions of atomic oxygen at 630nm. Such experiments will help quantify the coupling of the magnetosphere, ionosphere and thermosphere and will improve thermospheric density models.

5.4 Large-scale Magnetospheric Electric Field. Unlike the magnetospheric magnetic field, which penetrates to the ground, the dynamics of the large scale electric field in the ionosphere and magnetosphere cannot be deduced from the ground. A BARREL-like flotilla capable of measuring vector electric fields would allow for an instantaneous determination of the large scale magnetospheric electric field. There is no other cheap way to get direct, real- time, mapped-in-situ, large scale magnetospheric electric fields with 1 to 10 second resolution, and global, instantaneous coverage. Magnetospheric science is a system science often requiring multi-point measurements and coordinated measurements from different platforms. This holds true for studies of the global electric field, but also for other areas of research including particle precipitation, and ionospheric studies.

6 Education & Outreach

In a December 2018 report by the Committee on STEM Education (COSTEM) of the National Science & Technology Council, Charting A Course for Success: America's Strategy for STEM Education, three major objectives were identified for NASA: 1) foster STEM ecosystems that unite communities, 2) increase work-based learning and training through educator-employer partnerships, and 3) encourage transdisciplinary learning. While ballooning contributes to all three objectives it is the last one where ballooning has the most impact on STEM education. In fact, the report highlighted a NASA balloon platform as an exemplary example of transdisciplinary learning Thus, in addition to supporting multiple significant scientific objectives, ballooning contributes to the aerospace workforce development pipeline, enhancing public awareness of NASA programs, and training the next generation of scientists and engineers.

6.1 The Workforce Development Pipeline. Ballooning is a unique NASA capability that supports workforce development from K-12 through early career faculty and engineers. Scientific ballooning provides high quality, experiential projects for students from K-12 through graduate school that enables interdisciplinary STEM workforce training consistent with the COSTEM report objectives assigned to NASA. In addition, nation-wide programs making use of the established National Space Grant College

and Fellowship network, provide special opportunities to not only support workforce development but to also convey the advantages of scientific ballooning to new and large audiences.

6.2 Enhance the Public Awareness of Ballooning. For the August 21, 2017 North America total solar eclipse 54 teams from 32 states involving over 900 students were positioned across the path of totality from Oregon to South Carolina and flew payloads to an altitude up to 100,000 feet to downlink HD video of the moon's shadow on Earth that was live streamed over the internet. This effort, organized by the Montana Space Grant Consortium was an amazing success and was featured as part of NASA's eclipse coverage, which reached 600 million people. These kinds of projects engage the public, as well as students, exciting their imagination, and encouraging them to learn more about NASA ballooning.

6.3 Training Next Generation Scientists & Engineers. Balloon platforms are a critical vehicle for supporting PI-class academic research due to the A) short time scale between conception and flight results, B) relatively low cost, and C) recoverability. This combination of characteristics enables universities to support research programs that develop near-space flight hardware while engaging future scientists and engineers. As most balloon experiments are recovered and reflown the acceptable risk on individual balloon payloads should be high relative to spacecraft. By accepting risk on balloon payloads, quality assurance requirements are reduced which, in turn, will decrease development time and overall cost.

Recently, however, there is growing concern that safety and quality assurance requirements are increasing in the direction toward spacecraft mission requirements. If this trend is allowed to continue it is likely that the project time of development and cost will increase while access to the instrument by untrained students or early career faculty will decrease. These trends would have an adverse impact on training the next generation of scientists and engineers.

7 Balloon Technologies

Over time the sophistication and complexity of balloon payloads has steadily increased, in some instances potentially yielding scientific returns that can rival or exceed what can be accomplished in a much more expensive orbital mission. What ultimately limits the type and quality of the science that can be performed from a balloon platform is the altitude of the carrier balloon. In particular, high energy astrophysics experiments often require both high altitude and high suspended weight, as well as long flight times to increase the likelihood of detections. Similar statements can also be made for overcoming the absorptive and scattering/seeing effects of the atmosphere for payloads operating in the UV and optical. In the infrared and far-infrared, it is atmospheric water vapor that limits sensitivity. In all cases, the deleterious effects of the atmosphere decrease exponentially with height, making even modest increases in the altitude limits of carrier balloons capable of yielding significant increases in science return.

NASA qualified balloons come in two types, the standard zero-pressure balloon (ZPB) and the super pressure balloon (SPB). In the case of a ZPB, once it reaches its target altitude excess helium is vented, such that the balloon becomes in pressure equilibrium with its surroundings. Diurnal temperature variations then can lead to substantial altitude excursions which may necessitate the use of expendables (ballast and helium), limiting the time at float for a ZPB to approximately 1 to 2 months. In the case of an SPB, the balloon is made strong enough such that it can maintain a specific volume even when the helium within it is at a higher pressure than the surrounding atmosphere. This ability provides volumetric margin against changes in the temperature of the ambient atmosphere and can hold the altitude of the balloon constant without the use of expendables, thereby dramatically increasing an SPB's time at float (3+ months).

ZPBs can take as much as 4 tons into the low stratosphere (100,000 ft), but less than a ton into the high stratosphere ($> 160,000$ ft). To date, SPBs have only achieved modest sizes and suspended payload weight, 2 tons, restricting their

practical use to modest altitudes (110,000 ft). In order to realize the full scientific and cost saving potential of scientific ballooning, the development of larger zero pressure and super pressure balloons should be considered a high priority. Even now the demand for balloon flights outstrips the ability of NASA to launch them, either from mid latitude sites (e.g. Ft. Sumner, Palestine, or Wanaka) or polar regions (e.g. Antarctica and Sweden). At any given time, there is often a backlog of missions waiting for flight, which both delays the delivery of science to the community and increases its associated cost.

8 Findings/Recommendations

The Balloon Program analysis group makes the following findings and recommendations for NASA for the next decade of the scientific balloon program. These are presented in the order of the preceding sections, in which the disciplines were ordered alphabetically, not ranked by relative importance.

1. In this document, as we have noted in the introduction, the PAG has chosen not to advocate for a specific payloads to address the important NASA science questions across all of the Science Mission Directorate outlined above. The PAG does wish to emphasize the critically important role that NASA balloon missions play in generating cutting-edge science on short-time scale and at modest cost, in addition at advancing technologies and training future leaders for NASA space missions.

2. The PAG finds that several areas of scientific research would be greatly augmented with the development of one or more diffraction-limited near-UV, visible, near-IR, and/or thermal IR telescopes of up to 3 m on a balloon-borne platform. At IR wavelengths, there is a particular need for large aperture telescopes, although not necessarily ones with diffraction-limited image quality. The PAG recommend an active development program in three key areas to achieve this goal: thermal stabilization of optical assemblies, wavefront sensors to generate real-time in-flight wavefront errors, and a wavefront correction scheme (e.g.,deformable mirrors) to compensate for optical assembly aberrations.

3. The PAG commends the Balloon Program for the development of the Wallops Arcsecond Pointing System, and recommends building on this success to provide even better stabilization for potential observatory-class balloon-borne telescopes.

4. The PAG commends the Balloon Program for the continuing success and scientific impact of the Antarctic Long Duration Balloon (LDB) program flown out of McMurdo Station. The PAG recommends unwavering NASA support for this flagship program and its associated facilities near Williams Field, Antarctica. Antarctica represents a unique resource and environment for investigations across several disciplines and the opportunities afforded by the LDB merit such support. NASA should deploy a third payload building and commit to the resources necessary to sustain a three-large-payload per season launch rate.

5. The PAG welcomes recent increases in the NASA Astrophysics Research and Analysis funding and recommends that this increased funding for balloon payloads be advanced through the next decade given the need for increased payload complexity to address the scientific challenges summarized here.

6. The PAG commends the NASA Astrophysics Division and Balloon Program for developing and flight-qualifying the 60 Mcf conventional balloon and maturing the 18 Mcf super-pressure balloon, and the new launch facility in Wanaka, New Zealand, which supports SPB launches. The PAG recommends continued support for the growth of this facility, including a new payload integration building that could accommodate multiple payloads. These developments will enable new science investigations from Wanaka with science returns comparable to significantly more costly space flight missions, and complementing to NASA flagship missions.

7. The PAG recommends that NASA should provide a large-scale class of balloon investigation ($15-20M over 5 years) for highly meritorious and high-impact investigations. This new class is of particular importance for long-duration and ultra-long duration payloads that launch from Antarctica and Wanaka, NZ.

8. The PAG finds that a North American launch site that can provide reliable night-time launch opportunities is a high priority not only for Astrophysics balloon payloads, bu other disciplines as well. The PAG recommends that NASA identity and develop alternative launch sites in addition to Palestine, TX, and Ft. Sumner, NM.

9. The PAG recommends that NASA continue to advance the lift capability and float altitude of super pressure balloon to the point where it is commensurate with current zero-pressure balloon capabilities.

10. The PAG finds that commercial providers offer launch opportunities with station keeping and trajectory modification capabilities that may complement the NASA balloon program. These systems presently have small allowable payload sizes and weight, and lower altitudes than the NASA balloon program provides. While these capabilities do not currently meet Astrophysics payload requirements, they could be of use for Earth Science missions, and the PAG recommends that NASA engage with such providers and study opportunities that they may enable.

11. The PAG finds that while payload downlink bandwidth is improving, but is not keeping step with science needs. The science return of any mission can be significantly enhanced by higher data downlink capability, avoiding the possibility of data vault loss as a mission failure mode. By the end of the next decade, payloads will likely be capable of producing tens of Terabytes of science data in a 30-day flight. The PAG recommends that NASA pursue a cummunication downlink goal of 10 MB/s average through a flight, enabling a higher science return at lower mission risk.

12. The PAG recommends that NASA should engage with the National Space Grant College and Fellowship program to continue and expand strong support for student training ballooning programs that support the workforce development pipeline at all levels including K-12, university students, and in-service teachers.

13. The PAG recommends that NASA engage with stakeholders interested in the April 8, 2024 North American total solar eclipse as early as possible to assess scientific, workforce development, and public engagement projects, as well as payload weight classes including heavy payloads, and potential launch sites.

14. The PAG recommends that balloon project safety and performance standards applied to balloon missions should be reviewed at a level significantly below spacecraft standards. Such standards should be relevant to the project, avoid duplication of effort, be consistent with the need to provide novice personnel the flexibility to have direct involvement in the payload success. They should be associated with relevant, simple, concise, and straight forward best practices and safety training materials.

15. The PAG finds abundant evidence that expansion, not contraction, of the present portfolio of balloon flight options for both launch location and duration is important to the continued health of NASA astrophysics research, and the training of new investigators at every level. The PAG recommends that NASA increase the capacity of launch facilities, and more importantly and with the highest priority, the number of ground crews that can support them. NASA must also continue operations from locations that support research in auroral and radiation belt physics, and high latitude magnetosphere-, ionosphere-,and thermosphere-coupling, which are compelling scientific drivers in heliophysics and require flights at magnetic latitudes ranging from 55-70 degrees (e.g., Kiruna, Sweden).

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