PhysPAG Response to the Probe-Class Mission Charge

James J. Bock (Chair, Caltech/JPL), Marshall W. Bautz (MIT), Rachel Bean (Cornell), John W. Conklin (U. Florida) Neil J. Cornish (Montana State), Olivier P. Doré (JPL), Ralph P. Kraft (SAO), Henric Krawczynski (Washington U. St. Louis), Mark L. McConnell (U. New Hampshire), Amber D. Miller (Columbia), Igor V. Moskalenko (Stanford), Eun-Suk Seo (U. Maryland), Edward J. Wollack (GSFC)

Joint Statement

The COPAG, ExoPAG, and PhysPAG all agree that NASA should support the development of a probe class of competed missions for the Decadal survey. All three PAGs strongly support the first option proposed by Paul Hertz in his formal charge to the PAGs of January 14, 2016. Based on the input the three communities have received, there exists a wide range of community science goals that are both consistent with current National Academy priorities and that can be enabled with medium-class missions. The three PAGs also note that the work of preparing high quality white paper proposals to the 2020 Decadal Survey, for missions of this class, cannot be performed absent funding. In particular, all three PAGs agree that competed NASA HQ funds should allow at least 10 concepts for probe-class missions to be studied in some depth. However, the main concern associated with this first option is that limiting the funds available for each concept study to ~$100K will likely severely limit the veracity of the CATE analyses at this early phase, even though funds would be provided for more detailed CATE analyses when requested at a later phase by the Decadal Survey committee. We recommend that APD consider apportioning sufficient funds to carry out multiple CATE analyses that would apply to the general category of probe missions in advance of the Decadal Survey.

Charge to the PAGs

On 14 January 2016 the PAGs were charged to evaluate two options for developing probe-class missions for the Decadal survey:

1. Issue a solicitation through ROSES for Astrophysics Probe mission concept study proposals. The proposals will be evaluated via a peer-review process and APD will select a few (~10) for one-year studies. A modest (~$100K) amount of funding would be allocated for each study; cost assessment mechanisms would need to be discussed. The results of the studies would be presented to the Decadal Survey Committee. The Decadal Survey Committee would have the option of asking NASA to conduct further one-year studies at a higher level of detail (and at a higher cost for each study) for a small number (~3) of medium mission concepts.
2. Do nothing and let the community self-organize. Most likely this will result in submission of many white papers to the 2020 Decadal Survey from interested individuals and groups, as during the 2010 Decadal Survey.

Summary of PhysPAG Findings

1. We find broad and enthusiastic support in the PCOS community for furthering the development of probe-class missions, conceived as a new large mission class of the PI-led competed missions in the Explorer program. As an example of this enthusiasm, we have received 14 white paper concepts from the community spanning PCOS science themes that we attach as in Appendix A. We believe a scientific niche has been missing in the APD portfolio for competed, cost-capped missions in this price range. The success of the ESA M-class mission category testifies to the scientific effectiveness of such a program. We also note several NASA missions close to this cost point that have been successful in carrying out astronomical science (e.g. Fermi, Kepler, Spitzer). In the PCOS community, there is widespread support for the Explorer program in carrying out cost-effective science.

2. The PhysPAG endorses option 1 given in the charge, undertaking an initial study of ~10 1-year concept studies at ~$100k each, as an initial step.
3. However we are concerned that the cost information presented to the Decadal review will be insufficient. The initial $100k studies will not have the financial resources and schedule required to achieve the level of cost fidelity required by the Decadal. We feel the second step in option 1 "conducting further one-year studies at a higher level of detail (and at a higher cost for each study) for a small number (~3) of medium mission concepts" needs to take place well before the Decadal survey. Costing these mission concepts during the Decadal study may not be successful given the inevitable time pressure of a Decadal review. We note the past practice of the Decadal cost and technical evaluation (CATE) process, in evaluating the fidelity of well-defined costed missions, may be problematic for probe mission concepts developed from these preliminary studies. Our interactions with commercial cost modelers indicate that cost studies should incorporate input from non-NASA modelers early on, to assure better agreement with the Decadal CATE process, which further extends the duration and complexity of the studies.
4. We suggest that APD develop a second phase of studies to define costs for general probe missions, and to better determine the optimal cost point. Given the input we received on white papers, with many concepts in the lower end of the price range, it appears that certain concepts could fit well below the $1B total. If so, this would be an important finding for Decadal survey planning as it bears on the frequency of mission opportunities. While the cost studies may be best developed on specific scientific concepts, the findings must apply generally to the probe mission class.
5. We note that the Inflation Probe is unique in that it was recommended by the 2010 Decadal Survey. Studies for its development would directly apply to developing the probe mission category for the 2020 Decadal Survey.

Collection of Input from the Community

To respond to the probe charge issued by Paul Hertz on 14 January 2016, the PhysPAG collected community input on probe missions on several fronts.

- Prior to the charge from NASA, the PhysPAG organized a session at the AAS HEAD meeting in Chicago in 29 June – 1 July 2015 that featured presentations on probe concepts in high-energy astrophysics. Summaries of these concepts are provided in the PhysPAG response to the 2015 Facility mission charge (available on the PCOS website: http://pcos.gsfc.nasa.gov/docs/PCOS_facility_missions_report_final.pdf).
- After receiving the charge, the 3 PAGs held a joint open session at the AAS on 4 January 2016 seeking input from the community.
- At the PhysPAG EC meeting at the AAS, we scheduled a talk from Randy Persinger and Debra Emmons from the Aerospace Corporation to inform us as to the CATE costing process and suggestions for improving this process based on past experience from the 2010 Decadal review.
- On 27 January the PhysPAG issued a call for community 2-page white papers on probe mission concepts, which resulted in 14 submissions that were received in 1 March. Responses are attached in Appendix A.
- Selected members from the 3 PAGs held a telecon on 8 February to discuss coordination of a joint response to the charge. The PAGs chairs then coordinated responses and refined the joint statement by email.

Appendix A
White Paper Probe Concepts Submitted to the PhysPAG

The PhysPAG received 14 white paper submissions for 2-page probe mission concepts. A summary of these submissions is tabulated below. The full white papers follow.

Table: Summary of Probe White Paper Concepts Submitted to the PhysPAG

Name	First Author	Type	Spectral Range	Science	Cost	Launch & ops?
High-Energy X-Ray Probe (HEX-P)	F. Harrison	X-Ray	2-200 keV	Resolve X-Ray background, evolution of black hole spin, faint X-ray populations in nearby galaxies	$500M	Included
A Wide-Field X-Ray Probe	A. Ptak	X-Ray	~1-10 keV	Measure mass and spatial distribution of clusters and AGN, define LF of AGN	$540M / $740M	Not included
An X-Ray Grating Spectroscopy Probe	M. Bautz	X-Ray	5-50 Angstrom	Role of SMBH feedback in galaxy formation, distribution of hot baryons, characteristics of Galaxy's hot halo, GW counterparts	$784M	Included
AMEGO: A Medium-Energy Gamma-Ray Surveyor	J. McEnery	Gamma-Ray	0.2 MeV - 10 GeV	Time-domain GW counterparts, improved MeV surveying, nuclear line emission	$600-$800M	Included
Advanced Particle-Astrophysics Telescope (APT)	J. Buckley	Gamma-Ray	100 MeV - 50 GeV	Definitive dark matter search, all-sky transient survey, GW counterparts	Probe-class	Not stated
A Large Observatory for X-Ray Timing Probe (LOFT-P)	C. Wilson-Hodge	X-Ray timing	2 - 30 keV	Strong gravity and BH spins, matter in neutron stars, surveying the dynamic X-Ray sky, multi-messenger studies	$770M	Included
Death of Massive Stars (DoMaS)	P. Roming	Transients	X-ray/UV/IR	Study massive stars at reionization via GRBs and SNs.	$760M	Not stated

Table: Summary of Probe White Paper Concepts Submitted to the PhysPAG (continued)

Name	First Author	Type	Spectral Range	Science	Cost	Launch & ops?
Transient Astrophysics Probe (TAP)	J. Camp	Transients	X-ray/IR	Epoch of reionization from high-z GRBs and SNs, survey of the X-Ray sky, GW counterparts	$750M	Included
The Time-Domain Spectroscopic Observatory (TSO)	J. Grindlay	Transients	0.4 - 5 um	Epoch of reionization from high-z GRBs studies, growth of SMBHs over cosmic time, GW counterparts, transient discoveries	$650M	Included
GreatOWL: A Space-Based Mission for Charged-Particle and Neutrino Astronomy	J. Mitchell	Cosmic Ray	-	Nature of ultra-high energy cosmic rays, GZK-induced neutrinos	$540M	Not included
The Inflation Probe	NASA IPSIG	CMB	30 - 300 GHz	Inflationary gravitational wave background, reionization, large-scale structure, neutrinos	Probe-class	Not stated
Probe-Class Mission Concepts for Studying mHz Gravitational Waves	M. Tinto	Gravitational -wave	1 mHz – 10 Hz	Spiraling massive and super-massive black holes, BH formation, tests of strong gravity,distribution of white dwarf binaries	$560M / $900M	Not stated
A Probe-Class Gravitational-Wave Observatory	S. McWilliams	Gravitational -wave	1 mHz – 10 Hz	Massive BH binary mergers, stellar-mass BH and NS mergers, probe dark energy via z-L measurements	$830M - $1.2M	Included
99 Luftballons	T. Eifler	UV/Optical	270 - 1000 nm	Nature of dark energy, neutrino masses, tests of gravity	Not stated	ULDB

The High-Energy X-ray Probe (HEX-P)

White Paper for Probe-Class Astrophysics Mission Concept

P.I.: Prof. Fiona Harrison

California Institute of Technology • fiona@srl.caltech.edu • 626-395-6601

Co-I's: D.Stern, D.Alexander, S.Boggs, W.N.Brandt, L.Brenneman, D.Chakrabarty, F.Christensen, M.Elvis, A.Fabian, N.Gehrels, B.Grefenstette, J.Grindlay, C.Hailey, A.Hornschemeier, A.Hornstrup, V.Kaspi, H.Krawczynski, G.Madejski, K.Madsen, G.Matt, J.Miller, H.Miyasaka, S.Molendi, D.Smith, J.Tomsick, C.M.Urry, & W.Zhang

Summary: The *High-Energy X-ray Probe (HEX-P)* is a probe-class (~$500M) next-generation high-energy X-ray observatory with broadband (2-200 keV) response and ~40 times the sensitivity of any previous mission in the 10-80 keV band, and >500 times the sensitivity of any previous mission in the 80-200 keV band. Intended to launch contemporaneously with *Athena, HEX-P* will provide fundamental new discoveries that range from resolving ~90% of the X-ray background at its peak, to measuring the cosmic evolution of black hole spin, to studying faint X-ray populations in nearby galaxies. Based on *NuSTAR* heritage, *HEX-P* requires only modest technology development, and could easily be executed within the next decade.

We describe the *High-Energy X-ray Probe (HEX-P*; Harrison et al. 2011), a probe-class mission that will provide the natural successor to the *Nuclear Spectroscopic Telescope Array* Small Explorer (*NuSTAR*; Harrison et al. 2013), with a factor of ~40 gain in sensitivity and covering a wider bandpass. *HEX-P* is highly complementary to *Athena*, which emphasizes high-resolution spectroscopy and imaging below 10 keV. *HEX-P* achieves this with the larger effective area afforded by a Falcon 9 launch vehicle (compared to *NuSTAR*'s Pegasus launch vehicle). This allows three grazing incidence optics modules, each comprised of 390 shells, compared to *NuSTAR*'s two modules comprised of 133 shells. Combined with improvements in the optical designs and mirror mounting, *HEX-P* will have high spatial resolution (15″ half-power diameter; 4 times better than *NuSTAR*) and a broad energy coverage (2-200 keV; Figure 1 and Table 1). *HEX-P's* photon-counting detectors also offer timing resolution at the 0.1 msec level with count rate handling to 10^3 Hz. The mission will launch into a circular low-Earth orbit with near-equatorial inclination. Our rough order-of-magnitude (ROM) cost is $500M, including launch and 5 years of operations. *HEX-P* is intended to operate primarily as an point-and-stare observatory, with a funded, competitive Guest Observer program. All key *HEX-P* mission elements have strong *NuSTAR* heritage, with only modest technology development required. The mission could easily be executed within the next decade.

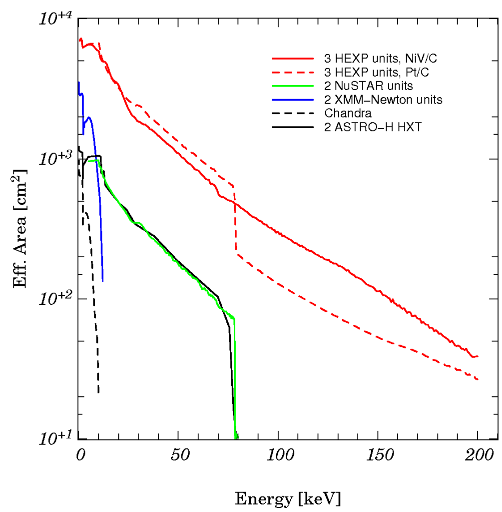

Figure 1. Effective area vs. energy for *HEX-P* and current/near-term focusing missions. We plot two potential recipes for the *HEX-P* mirror coatings: Pt/C is the recipe currently used by *NuSTAR*, while NiV/C would require some modest development.

The combination of wide bandpass and high-energy sensitivity will allow *HEX-P* to revolutionize our understanding of both Galactic and extragalactic black holes in the Universe, achieving science that cannot be done with existing or currently planned facilities. If developed and launched on a similar timescale to *Athena*, *HEX-P* would support simultaneous observations, greatly enhancing *Athena*'s ability to, for example, understand the detailed physics of black hole accretion and hot, merger-driven shocks in clusters — both systems have continua extending to high energy that must be properly modeled to interpret their spectra. The broad-band continuum measurements performed by *HEX-P*, both on their own and in conjunction with *Athena*, are critical for key Physics of the Cosmos (PCOS) science objectives: *When and how did supermassive black holes grow?, What happens close to a black hole?,* and *How does large scale structure evolve? HEX-P* will also address a broad range of additional objectives, from studying binary populations in nearby galaxies to understanding the mechanisms that drive supernova explosions. In particular, as a natural follow-on to *NuSTAR*, *HEX-P* addresses science that is not planned by any flagship-class missions, and is beyond the capability of an Explorer-class mission. *HEX-P* science is clearly in the realm of a Probe-class mission.

Parameter	*HEX-P*	*Athena (X-IFU)*	*NuSTAR*
bandpass	2 - 200 keV	0.3 - 12 keV	3 - 79 keV
angular resolution [HPD]	15″	5″	58″
spectral resolution [FWHM]	250 eV @ 6 keV 600 eV @ 60 keV 1 keV @ 122 keV	2.5 eV @ 6 keV	400 eV @ 6 keV 900 eV @ 60 keV
timing resolution	0.1 msec	—	0.1 msec
field of view	13′ × 13′	5′ × 5′	12′ × 12′

Table 1. Key performance parameters.

Black Hole Growth over Cosmic Time. A complete census of AGN activity is the backbone behind any attempt to understand the mass accretion history of the universe, and the relationship between accretion and star formation. Deep surveys with *Chandra* and *XMM-Newton* resolve only ~75% of the 6-10 keV background and are missing the vast majority of the most heavily obscured AGN ($N_{\rm H} > 3\times10^{23}$ cm^{-2}). Importantly, models suggest that the most heavily obscured AGNs represent a key early and rapid black hole growth phase. Sensitive mid-IR observations and stacking analyses from deep X-ray surveys imply that the space density of heavily obscured AGNs is large (e.g., Stern et al. 2005, Treister et al. 2010) while theoretical models suggest that they represent a growth phase that is qualitatively different from less obscured AGN. However, we currently lack definitive measurements of their space density and properties. Observations with *NuSTAR* now directly resolved ~35% of the background at its ~20 keV peak (Harrison *et al.* 2016), but are unlikely to significantly surpass this level given issues of sensitivity and source confusion. With its 4× improvement in resolution and order-of-magnitude increase in effective area, *HEX-P* will extend this science with significant samples of heavily obscured AGN out to high redshift, uncovering new AGN source populations and resolving ~90% of the X-ray background at its peak.

Black Hole Accretion Physics. X-ray observations of AGN above 10 keV provide a critical complement to the more standard 0.5-10 keV window, allowing more precise constraints to be placed on the physical properties of the black hole, corona, and accretion disk. As demonstrated by *NuSTAR*, studies that extend beyond 10 keV provide the most robust measurements of black hole spin (*e.g.*, Risaliti *et al.* 2013), as well of the temperature and structure of the X-ray emitting corona (*e.g.*, Fabian *et al.* 2015 and references therein). However, *NuSTAR* is unlikely to provide spin measurements for more than a few dozen local Seyfert galaxies, and the coronal measurements are based on subtle continuum downturns at ~50 keV used to infer cut-off temperatures of ~100 keV and higher. *HEX-P* will be revolutionary in these regards, providing robust black hole spin measurements for statistically significant samples of objects over a range of luminosities, out to cosmological distances. *HEX-P* will also provide robust measurements of high-energy spectral cut-offs, which probe the temperature and geometry of the poorly understood corona. In addition, broad-band high-energy campaigns will probe whether the corona is outflowing and/or extended (*e.g.*, Zoghbi *et al.* 2014, Wilkins & Gallo 2015). Though a model in which the corona is an atmosphere to the inner accretion disk is still viable, many of the *NuSTAR* observations to date are well described by the so-called "lamppost model", which considers the corona to be a compact source that can move along the spin axis of the black hole (e.g., Parker *et al.* 2014). While *NuSTAR* has begun such investigations for the nearest, brightest Seyferts, *HEX-P* will characterize the corona over a broad range of black hole mass and accretion rate, reaching out to cosmological distances.

Other Objectives. With its revolutionary increase in sensitivity, *HEX-P* will be an extremely capable and flexible platform, enabling a broad suite of additional science programs. For example, *HEX-P* will extend hard X-ray studies of the local universe to fainter levels, enabling the identification (rather than simple detection) of large numbers of compact objects (*e.g.,* black holes, neutron stars, ultraluminous X-ray sources, and white dwarfs) in our Galaxy and nearby galaxies. By studying regions with different star formation rates, metallicities, and ages, *HEX-P* will provide unique information on the how star formation proceeds in different environments. As one other example, *HEX-P* will be sensitive to the 158 keV ^{56}Ni line in supernovae, as well as Compton-scattered continuum from higher energy γ-ray lines. *HEX-P* will be sensitive to SNe Ia within ~70 Mpc, corresponding to a supernova rate of ~40 per year. The flux and spectral shape of the γ-ray line and hard X-ray continuum are sensitive to both the overall nucleosynthesis and the amount of mixing in the ejecta, allowing us to address fundamental questions about supernovae, from their progenitor systems to how the nuclear flame propagates.

References • Fabian *et al.* 2015, MNRAS, 451, 4375 • Harrison *et al.* 2011, http://pcos.gsfc.nasa.gov/studies/rfi/Harrison-Fiona-RFI.pdf • Harrison *et al.* 2013, ApJ, 770, 103 • Harrison *et al.* 2016, ApJ, submitted (arXiv:1511.04183) • Parker *et al.* 2014, MNRAS, 443, 1723 • Risaliti *et al.* 2013, Nature, 494, 449 • Stern *et al.* 2005, ApJ, 631, 163 • Treister *et al.* 2010, ApJ, 722, 238 • Wilkins & Gallo 2015, MNRAS, 449, 129 • Zoghbi *et al.* 2014, ApJ, 789, 56

A Wide-Field X-ray Probe

A. Ptak (NASA/GSFC; andrew.ptak@nasa.gov) for the N-WFI and WFXT teams

The two highest-priority large projects recommended by the New Worlds, New Horizons (NWNH) Decadal survey are WFIRST and LSST, both survey missions. Both of these projects are slated to start operations in the mid-2020s. There is no complementary X-ray survey capability planned that would match these missions in survey area and depth. While eROSITA will survey the entire X-ray sky and effectively find all massive clusters of galaxies, the ~ 30" survey-averaged PSF would preclude much of high redshift science. In order to effectively probe the growth of both supermassive black holes, particularly obscured black holes, and groups and proto-clusters at z>1, a dedicated, sensitive X-ray survey mission is required. Good angular resolution is required to give a low background for source detection, minimize source confusion, give precise source positions for identifying unique optical/IR counterparts, and distinguish point from extended sources. Here we discuss two similar wide-field X-ray mission concepts, the Wide-Field X-ray Telescope (WFXT), which was submitted to NWNH and studied in 2013 by the MSFC Advanced Concepts Office, and N-WFI, one of the three notional missions studied in the 2012 NASA X-ray Mission Concepts Study[1]. Both of these concepts have requirements of a large FoV (at least 24' for N-WFI, 1 degree for WFXT), good angular resolution (5-10" averaged over the FoV) and effective area of at least 5000 cm^2 at 1 keV (with a goal of 10,000 cm^2). N-WFI also has an effective area requirement of 1,800 cm^2 at 6 keV to enable Fe-K science in (nearby) AGN, resulting in a focal length of 6 m for N-WFI (the WFXT design focal length is 5 m).

Measurements of the mass and spatial distribution of clusters of galaxies to z~2, along with the spatial distribution of AGN will definitively address the *IXO* science objective, "*How does large scale structure evolve?*" By defining the luminosity function of AGN as a function of redshift (to z ~ 6), notably including obscured AGN often missed by other surveys, and determining the host galaxy properties and environment, the *N-WFI* or *WFXT* surveys will answer the *IXO* question, "*When and how did supermassive black holes grow?*" The large numbers of clusters and groups of galaxies that would be detected (~ 10^5) with good angular resolution will reveal the role of AGN outbursts in their formation and evolution, and how this may change as a function of redshift which will address the *IXO* science objective, "*What is the connection between supermassive black hole formation and evolution of large scale structure?*"

An X-ray survey probe would also study the growth and evolution of clusters of galaxies by carrying out sensitive large-area surveys with sufficient depth to detect clusters and groups to redshifts of at least 2–3. The angular resolution of ~ *5"* will permit cluster recognition and allow the cores to be excised for measurements of cluster properties (to eliminate the possibility of spectral contamination by a central AGN). For high-z clusters, which will be detected by SZ surveys and WFIRST/LSST, X-ray observations remain critical for mass calibration and ICM physics. The detection of groups at high redshifts will inform the merger history of clusters and their growth. The impact of environment on galaxy evolution (e.g., inside or outside of clusters and groups) will be studied using the very large samples obtained in these surveys.

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[1] http://pcos.gsfc.nasa.gov/studies/x-ray-probe-2013-2014.php

N-WFI or WFXT would also detect millions of AGN in medium and deep survey areas. A large number of AGN will be detected at high redshift (z > 6), although predictions vary by orders of magnitude. These X-ray surveys would place critical constraints on the total AGN population at z>6, while optical/NIR surveys will be biased towards detecting only unobscured AGN. Synergy with WFIRST (e.g., the obvious medium-depth survey area would overlap with the WFIRST HLS areas) and LSST would enable photometric and spectroscopic redshift determinations at high z. As shown in Figure 1, planned Athena WFI surveys will result in much smaller survey areas than would be needed to properly match the surveys of LSST and WFIRST.

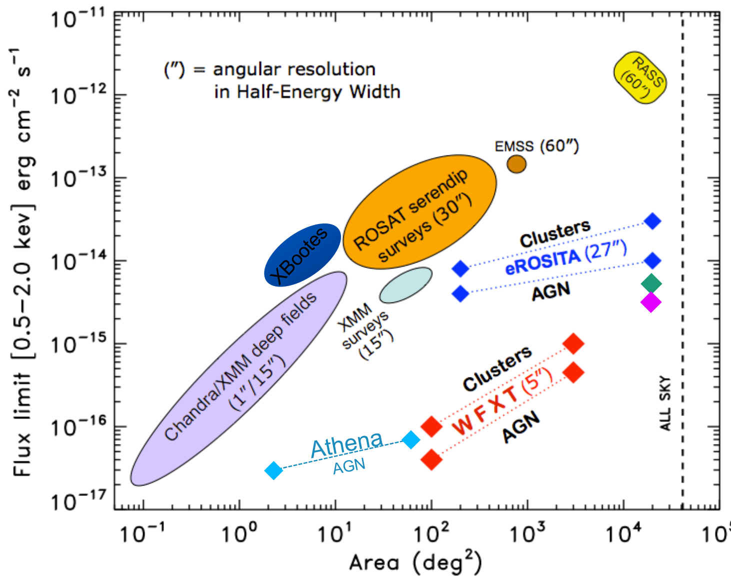


Figure 1: Area vs flux limit for current and planned X-ray surveys, with WFXT and Athena WFI surveys also marked.

Development in X-ray optics over the past decade has made lightweight, 5” X-ray optics a reality, and by the end of the decade one or more of the active areas of development may result in optics with an on-axis PSF of ~ 1” or better. Thus it may be possible to achieve an optical design/survey strategy with an on-axis PSF of 1-2” while maintaining a field-averaged PSF of 5-10”. No other significant technology developments are needed for an X-ray survey probe mission. Advances in rapid readout technology with either traditional CCDs or active pixel sensors would improve the timing capability of the mission (most relevant in a guest observer/pointed phased of the mission) and reduce the need for optical blocking filters. Including a rapid slew capability would enable higher observing efficiency in low earth orbit and, along with a large field-of-regard, enable rapid response to targets of opportunity such as gravity wave detections and exotic LSST triggers. A large field of view, high effective area and sharp PSF would all be required to effectively acquire and monitor the EM counterpart to gravity wave sources and test competing physical models for their origin.

Both the ACO WFXT and PCOS N-WFI studies estimated costs well below $1 billion. The N-WFI cost estimate was $742M excluding launch costs ($210M was assumed for the launch). The ACO WFXT cost estimate was $541M. Mission lifetimes of 3 years (N-WFI) and 5 years (WFXT) were assumed.

An X-ray Grating Spectroscopy Probe

M. W. Bautz[1], J. A. Bookbinder[2], W. N. Brandt[3], J. N. Bregman[4], L. Brenneman[5], C. Canizares[1], L. R. Corrales[1], A. Foster[5], H.M. Günther[1], D.P. Huenemoerder[1], R.L. McEntaffer[6,*], R. Petre[7], A.F. Ptak[7], R.K. Smith[5], W.W. Zhang[7]

In the discussion of the International X-ray Observatory (IXO) in New Worlds, New Horizons, two key instrumental capabilities were identified for meeting the scientific objectives. These were an X-ray calorimeter array and an X-ray grating spectrometer. ESA's Athena mission incorporates a calorimeter with capabilities comparable to those planned for IXO, but it is lacking a grating spectrometer. While an Explorer class grating mission (effective area ~500 cm^2, $\lambda/\Delta\lambda \sim 2500$) can address many of the IXO science objectives, an X-ray Grating Spectroscopy Probe (XGS-P) providing higher spectral resolving power ($\lambda/\Delta\lambda > 5000$) and higher throughput (effective area > 1000 cm^2) in the soft X-ray band (5-50 Å) could fully achieve and go beyond the IXO science objectives. A partial list of key science questions, along with how XGS-P can address them follows:

1. ***What is the role of matter and energy feedback from supermassive black holes in the evolution of galaxies?***
   a. XGS-P would be capable of exploring the full range of ionization states and density characteristics of SMBH accretion disk winds on recombination timescales of thousands of seconds, thus sensitively probing time variation in these winds. Furthermore, current grating studies under-resolve the spectral complexity of ionized absorbers, which is evident at other wavelengths, but not yet realized for X-rays. The >5 factor of improvement over existing observatories in spectral resolving power can study absorption line profiles in depth to uncover wind dynamics. Such studies can occur on hundreds of AGN over many absorption lines such as the K-shells of C, N, O, and Ne, as well as the L-shells of Si and Fe while only a small number of bright AGN on longer time scales would be possible with the capabilities in an Explorer mission.
   b. Studying density-sensitive lines such as Fe XX, XXI, and XXII can accurately trace the launching radius of the wind which is currently unknown and key to understanding the physical mechanisms of this feedback.
   c. Emission lines of the Fe L-shell will probe the relativistic inner disk conditions in some of these systems and provide insights into the environments adjacent to the central supermassive black hole.
   d. Resolving down to the thermal limit (~ 50 km/s) for photoionized plasmas would open new diagnostics for the physics of outflows driven from black hole systems.
2. ***What is the distribution of hot baryons?***
   A significant fraction of baryonic matter and metals in the Universe are thought to exist in hot (10^{6-7} K) gas in the outskirts of galaxies and clusters, comprised of both infalling material that never formed into dense structures as well as material expelled via outflows from supermassive black holes, although the relative strength and importance of each process remains uncertain. Only a grating spectrometer can detect the metals in this hot gas via absorption lines of C and O to determine how the gas density and temperature vary with galactocentric (or cluster-centric) radius. With XGS-P, equivalent widths down to below 2 mÅ could be measured, enabling measurements of multiple ions along each line of sight, constraining both abundances and temperatures.
3. ***What are the basic characteristics of our hot Galactic halo?***
   a. Using X-ray absorption spectroscopy, XGS-P can measure the abundances of C, N, O, and Ne, along with the heavier elements Si, S, and Fe. These relative abundances will determine SN type progenitors which is key to determining the halo's origin.
   b. Measurements of C V absorption will be possible for the first time, which, when combined with O and N measurements, will determine the temperature distribution of the halo.
   c. The high spectral resolving power of XGS-P will allow derivation of a rotation model for the halo and characterize the angular momentum distribution. The radial dependence on rotation provides information on the origin of the halo and its interaction with Galactic fountains.
4. ***What are the characteristics of the solid phase of material along the line-of-sight to extragalactic sources?***
   a. Soft X-ray absorption spectroscopy can concurrently address both gas and dust abundances unlike any other wavelength band. Absorption and scattering fine structure at the O-K, C-K, and Fe-L edges can be compared to laboratory dust analogs to determine grain compositions and properly constrain dust grain models. The details in these features can only be seen through the combination of spectral resolving power and effective area offered by XGS-P.
   b. Such studies are crucial to understanding foreground linear polarization in CMB measurements, the dust torus intrinsic to AGN, and extragalactic dust in the foreground to XGS-P sightlines.
5. ***How do young stars accrete?***
   High spectral resolving power is necessary to separate contributions from coronal emission, accretion processes, and outflows. Only when combined with large effective areas, such as those offered by XGS-P, can

*Contact author: randall-mcentaffer@uiowa.edu, Affiliations: 1. MIT, 2. NASA's Ames Research Center, 3. Penn State University, 4. Univ. of Michigan, 5. Harvard-Smithsonian Center for Astrophysics, 6. Univ. of Iowa, 7. NASA's Goddard Space Flight Center

a complete study of line ratios be performed on a substantial sample of young stars. Accessing He-like triplets such as Mg XI, Ne IX, OVII, and, for the first time, CV will provide necessary constraints on accretion models.

6. ***What are the dynamics of hot star winds?***

   XGS-P will be able to resolve structure present in the strong emission lines from C, N, O, Ne, Mg, and Fe. This structure evolves on the timescale of hours and produces broad lines with distinct profiles. The line profile structure is affected by inhomogeneities in the wind and acceleration of the plasma, while being dependent on the radius of formation. Fully resolving this structure in a wealth of lines will allow determination of where X-ray emitting shocks are formed, characterizing the dynamics within these winds.

7. ***How do extreme events in our Universe evolve over time?***

   a. LIGO's first detection of gravitational waves (GW) opened a new door of scientific discovery. Typical GW sources are expected to be mergers of two neutron stars which should generate a gamma ray burst and possibly emission from magnetar-powered ejecta. The XGS-P would be sensitive to the faint spectral features in the spectrum of either the direct or scattered X-rays during the afterglow of the source, thus allowing characterization of this GW counterpart.
   b. X-ray flares in galaxies can be attributed to tidal disruption of a star by the central supermassive black hole. These tidal disruption events can be observable for months to years. The XGS-P can perform detailed spectroscopy to measure the temperature, abundance, velocity, and ionization state of this plasma and do so over multiple observations to trace the evolution of the disrupted stellar material.

A concept probe study for a Notional X-ray Grating Spectrometer (N-XGS) was completed earlier this decade and is included in the NASA X-ray Mission Concepts Study Project Report, August 2012 (http://pcos.gsfc.nasa.gov/studies/x-ray-mission.php). The optical design of XGS-P would be very similar to that of N-XGS, but could also take advantage of recent developments in X-ray mirror, grating, and detector technologies.[1] The instrument suite would likely consist of two or more independent, objective grating spectrometers operating in parallel. The telescope would have a modular design with several azimuthal sectors contributing to the total collecting area. Each sector would feed an array of gratings that disperse the spectrum onto an array of CCDs. The modular design maximizes spectral resolving power by only sampling a fraction of the total telescope PSF (subaperturing) while also allowing for increased effective area through the incorporation of multiple independent spectrometers.

The performance requirements for XGS-P ($\lambda/\Delta\lambda > 5000$, effective area > 1000 cm^2, bandpass <2 keV) could be realized in the near future through existing technologies. X-ray telescope technologies are rapidly advancing, and methods such as those using slumped glass optics are capable of fabricating and aligning mirrors to reliably produce Wolter-I telescopes with PSFs < 10", HEW. Slumped glass optics from GSFC are at a TRL of 4 and would be a feasible and technically sound choice for XGS-P. Furthermore, two grating technologies – off-plane reflection gratings and critical angle transmission gratings – are also being developed through PCOS programs, clearing a TRL of 4 with a clear path to TRL 5. The detectors would be composed of CCDs and electrical subsystems similar to those used on previous X-ray missions and are already at a high TRL as a result. System level tests incorporating these technologies are already planned and will reduce the most critical technical risk for a Probe mission. Even though developments are currently being made in all the key areas for a grating spectroscopy probe, mission specific developments to reach TRL 6 would still take time given the different focal length, module size requirements, alignment budgets, etc. that will be specific to the final design and unique from what is currently being developed.

A proper study of an XGS-P capable of achieving the science goals listed above is necessary to accurately assess cost and spacecraft requirements. This study should be performed after a conceptual design is formulated using the state-of-the-art for the various spectrometer technologies. However, a rough order of magnitude cost and estimate of mission requirements for XGS-P can be based upon the previous N-XGS study, which had similar optical designs and spacecraft demands. Costs drivers such as mass, power, and launch vehicle are similar and the cost study performed for N-XGS can be used as a basis for XGS-P. This cost came out to be $784M, including reserves. This is dominated by the Payload (~$166M), Spacecraft (~$229M), and Launch Vehicle ($140M) with the remainder divided between the other various WBS elements. The N-XGS basis for spacecraft requirements includes a mass of 828 kg, power of 646/1451 W (observing/peak), 10 Mbps downlink, and 58 Gbit of storage. These numbers include 30% contingency. The prime mission would have a lifetime of 3 years and a goal of 5 with an orbit at L2 after being delivered by a Falcon 9 vehicle. Pointing requirements include control of 45" over 200 ks, knowledge of 1.3" (3σ, per axis), and jitter of 0.2" RMS for frequencies above 15 Hz.

All-sky Medium Energy Gamma-Ray Observatory (AMEGO): A Medium-Energy Gamma-ray Surveyor

Julie McEnery, Elizabeth Ferrara, Elizabeth Hays, John Mitchell, Alex Moiseev, Roopesh Ojha, Jeremy Perkins, Judith Racusin, Andrew Smith, David J. Thompson (NASA/GSFC), Marco Ajello, Dieter Hartmann (Clemson University), James Buckley, Henric Krawczynski, Fabian Kislat (Washington University), Regina Caputo, Robert Johnson (UCSC) Valerie Connaughton (USRA) J. Eric Grove, Richard Woolf, Eric Wulf (NRL) Luca Baldini (University and INFN/Pisa), Nicola Omodei (Stanford) Michelle Hui, Colleen Wilson-Hodge (NASA/MSFC)

MOTIVATION

The MeV domain is one of the most underexplored windows on the Universe. From astrophysical jets and extreme physics of compact objects to a large population of unidentified objects, fundamental astrophysics questions can be addressed by a mission that opens a window into the MeV range. The time is right for an MeV mission. *Fermi*-LAT observations at GeV energies have opened a window to a rich and varied ensemble of astrophysical sources, and demonstrate the promise of an equally rich return from opening the MeV band. Secondly, we are at the dawn of the multimessenger era, with the recent discovery of high energy astrophysical neutrinos by IceCube and the first direct observation of gravitational waves by LIGO. By virtue of its focus on extreme environments, a medium energy gamma-ray surveyor is an excellent partner in these new scientific endeavors.

AMEGO will provide unprecedented advances in three areas of MeV astrophysics, 1) time domain astrophysics in the MeV regime, probing particle acceleration in a broad range of galactic and extragalactic objects, 2) deepest view of the entire MeV sky addressing the many new questions raised by *Fermi*. This is particularly relevant in the MeV energy band where most *Fermi* sources emit their peak power, 3) exploration of the nuclear line universe, probing the creation of key elements created in explosive and dynamic astrophysical environments.

TECHNICAL CAPABILITIES

Instrument: AMEGO will detect gamma-rays via Compton scattering at low energies (<~10 MeV) and pair production at higher energies (~>10 MeV). In the Compton regime, the use of solid state technology provides substantial performance improvements relative to COMPTEL, the Compton telescope flown on the Compton Gamma-Ray Observatory (CGRO). In the pair regime, AMEGO has been optimized for peak performance at lower energies relative to Fermi-LAT by minimizing passive material (e.g. conversion foils) in the tracker and enhancing low energy readout in the calorimeter.

Energy range	0.2 MeV − >10 GeV
Angular Resolution	3º (1 MeV), 10º (10 MeV),
Energy Resolution	<1% below 2 MeV; 1-5% at 2-100 MeV; ~10% at 1 GeV
Field-of-View	2.5 sr
Sensitivity (MeV s^{-1} cm^{-2})	4×10^{-6} (1 MeV); 4.8×10^{-6} (10 MeV); 1×10^{-6}(100 MeV)

Observatory: AMEGO will operate in low-earth orbit in two modes: a survey mode covering a large fraction of the sky every orbit and an inertially pointed mode. The large field of view allows a loose pointing requirement (~5°) with a requirement on pointing knowledge of ~20".

INSTRUMENT TECHNOLOGIES

AMEGO will consist of four hardware subsystems: a double-sided silicon strip tracker with analog readout, a segmented CZT calorimeter, a segmented CsI calorimeter and a plastic scintillator anticoincidence detector. Examples of each of these detector types have already been flown.

This instrument primarily makes use of flight-proven technologies (e.g., *Fermi*-LAT, AGILE, PAMELA, and AMS) and optimizes the energy resolution for MeV line studies through development of the CZT calorimeter configuration and accompanying dedicated electronics, for which development typically takes a couple years.

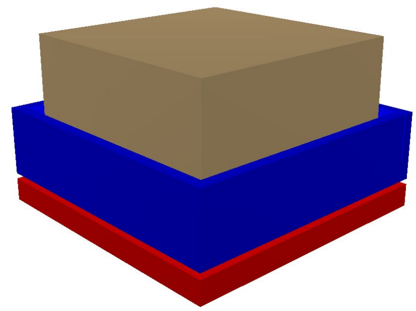


Figure 1: The AMEGO instrument subsystems: CsI calorimeter (red), CZT calorimeter (blue), Si-tracker (brown), ACD (not shown).

REASONS WHY A PROBE-CLASS MISSION IS NEEDED

An MeV gamma-ray surveyor probe mission has a unique capability to provide sensitive coverage of both the Compton (0.2 - 10 MeV) and pair conversion (10 MeV - 10 GeV) regimes. This allows a single mission to cover the entire gap between the current generation of hard X-ray instruments and the *Fermi*-LAT.

Enhancing the performance of the calorimeter for Compton events will open up new capabilities for MeV spectroscopy. AMEGO will address three key performance directions in MeV astrophysics. We will have an outstanding continuum sensitivity over a wide energy range and field of view to continue *Fermi*-LAT-like science down to lower energies. In addition we add a substantial science case from nuclear line astrophysics.

A smaller scale mission could not cover the entire energy range, and would necessitate a choice between a wide-field continuum sensitivity and nuclear line spectroscopy. With AMEGO we can do both.

AMEGO will have the very broad science menu appropriate for a probe class mission. As an all-sky surveyor it will collect data on all MeV sources in the sky and will provide a service to the whole astrophysical community.

COST ESTIMATE

The payload cost of $150M (not including contingency) has been derived by scaling a price-H cost estimate for a similar instrument. Adding contingency and rough estimates for spacecraft and launch vehicle, this results in a cost of $600-$800M, well within the bounds of a probe class mission.

Advanced Particle-astrophysics Telescope (APT)

James H. Buckley* (buckley@wustl.edu), W. Robert Binns*, Viatcheslav Bugaev*, Manel Errando*, Martin Israel*, Fabian Kislat*, Henric Krawczynski*
Washington University, One Brookings Dr., St. Louis, MO 63130

The *Advanced Particle-astrophysics Telescope* (APT) is a concept for a future space-based γ-ray mission that would provide an order of magnitude improvement in sensitivity in the 1 MeV to 50 GeV range compared with Fermi or any existing (or proposed) Compton telescope. The straw-man concept makes use of multiple layers of long scintillating fibers and thin CsI tiles covering a large passive area of 3m$\times$6m. With a thickness of < 4 radiation lengths, the concept trades energy resolution and high-energy reach for a very large effective area and nearly all-sky coverage. This trade-off would result in an optimal design for the primary science drivers: identifying dark matter and revealing the nature of gravitational wave sources and short γ-ray bursts. By replacing the passive converter layers (e.g., the tungsten foils employed in pair-production telescopes) with imaging CsI detectors, the instrument will function both as a pair telescope for 100 MeV to $\sim$50 GeV γ-rays and as a Compton telescope with excellent sensitivity down to MeV energies. At GeV energies where effective area begins to become the dominant factor determining sensitivity, the much larger geometry factor of the instrument would result in an order of magnitude improvement in sensitivity compared with Fermi. While the Compton angular and energy resolution would be somewhat limited, the enormous effective area would result in an improvement in sensitivity in the $\sim$MeV to 100 MeV regime by orders of magnitude compared to any extant instrument. In the Compton regime, the higher detection statistics would more than compensate for a degradation in angular resolution for localization of short transients. Another unique feature of the instrument concept is incorporation of transition radiation detectors (TR) by adding passive multi-layer radiators as part of the fiber support structure. While the idea lacks an experimental demonstration, preliminary calculations and past studies (for cosmic-ray experiments) indicate that with the use of high-energy TR detectors (with thick TR converter layers and CsI detectors for >100 keV X-rays) the instrument could potentially extend energy measurements up to electron energies of 50 GeV [3][4] but with only 3 radiation lengths of CsI (see Fig. 1). The up-down symmetry of the detector layers would also allow particles to enter from the top or bottom of the instrument, providing close to a 4π sr field of view for a high orbit.

The primary science goals for the mission are to conduct a definitive search for dark matter, and to provide instantaneous nearly all-sky coverage (with a $\sim 10im^2$ effective area) to search for the signals from short γ-ray bursts and gravitational wave sources. Analysis of Fermi LAT data on dwarf galaxies results in some of the most powerful constraints on generic models of WIMP dark matter up to >100 GeV masses [1] and underscores the important role of indirect detection on solving the dark matter problem. With more than an order of magnitude improvement in the exposure factor for dwarf galaxies in the GeV range and with extended coverage of the continuum spectrum down to MeV energies, APT will be able to rule out the entire natural parameter space for a thermal WIMP up to TeV mass scales. At mass scales above $\sim$1 TeV the continuum spectrum will reach hundreds of GeV where ground-based instruments like CTA can be used more effectively to detect the continuum γ-ray emission. Moreover, annihilation line features are more effectively probed by ground-based experiments like CTA down to even lower masses (down to $\sim$100 GeV). Acknowledging the important role of ground based experiments, the philosophy of trading maximum energy and energy resolution for a larger geometry factor is likely to lead to the optimum DM search strategy. While the design is driven by dark matter science, this design also makes a number of secondary scientific objectives possible.

The recent discovery of gravitational waves by the LIGO collaboration [2] points to the importance of instantaneous all-sky coverage to detect electromagnetic counterparts needed to localize these events. The γ-ray band is one of the few wavebands (over the entire electromagnetic spectrum) in which true instantaneous all-sky coverage is possible. The very large effective area of APT in the MeV to multi-GeV regime would be ideal for detecting GeV emission from short γ-ray bursts or the MeV to GeV counterparts from gravity wave sources. A larger GeV FoV and larger MeV effective area could offer a great improvement in the capability of APT compared to Fermi. For GRBs, Fermi has only seen the brightest events near the high end of the fluence distribution; thus the dramatic improvement in effective area is as (or more) important as the larger instantaneous field of view.

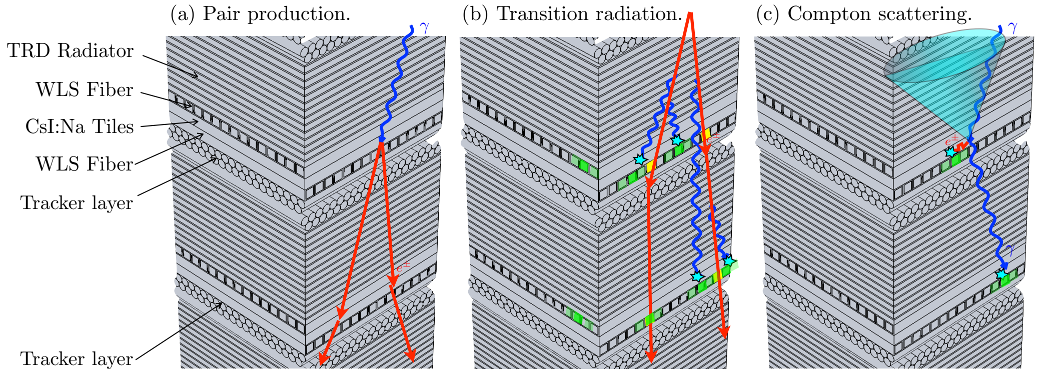


Figure 1: Cross section of APT showing 2 of the 20 layers, and demonstrating: (a) Pair telescope mode where a primary γ-ray pair produces and the $e^- + e^+$ pair are tracked in subsequent hodoscope layers; (b) Transition radiation mode where Lorentz-factor measurements of the electron and positron from a pair or a primary cosmic-ray are provided by the TR radiator and CsI hard X-ray detector; and (c) Compton telescope mode where one or more Compton scatters is followed by total absorption of the Compton gamma. Dark blue indicates photons (γ-rays or X-rays), red indicates charged particles (e.g., electrons and positrons, blue stars indicate energy deposition in the CsI, and green indicates light collected by the WLS fibers. The blue cone in figure (c) represents the reconstructed arrival direction for a Compton telescope measurement.

Another, secondary capability of the instrument also has a bearing on the primary dark-matter science driver, but through the detection of charged cosmic rays rather than γ-rays. The use of a transition radiation detector to reduce the instrument mass for γ-ray measurements will also provide measurements of cosmic-rays with energies approaching the knee in the all-particle spectrum. In particular, this capability could result in the measurement of the secondary to primary ratio of cosmic rays up to $\sim$100 TeV energies providing a critical data needed to understand cosmic-ray propagation, and to properly interpret cosmic-ray positron and antiproton measurements.

We describe a straw-man technical approach for APT that could achieve the order of magnitude improvement in sensitivity compared with Fermi at about the same total mission cost. The key to making this possible is the use of long scintillating fibers, and new solid-state high-QE photodetectors. The tracker layers would be formed of interleaved layers of round scintillating fibers for high detection efficiency (>30 photoelectrons for a minimum ionizing particle in a 1.5mm fiber). Limited pulse-height information from two layers could be used to centroid much better than the fiber pitch reaching an RMS resolution of around 250μm. The larger area of the instrument translates to a larger separation in the fiber planes for a given geometry factor, reducing the geometric contribution to angular resolution. In place of passive converter layers, CsI detectors would be used. Green wavelength shifting fibers covering thin sodium-doped CsI tiles could be used to shift the blue emission from the CsI:Na and pipe a fraction of the isotropically re-emitted light to the SiPM photodetectors. The relatively fast signals from ionization in the plastic WLS fibers could be discriminated from the relatively slow signal from ionization or X-ray absorption in the CsI:Na. Centroiding the light collected by the fibers would provide the $x - y$ coordinates of the interaction, and the spread of the light could be used to determine the depth of interaction. The use of long scintillating fibers read out at the edges of the instrument with solid-state photosensors (SiPMs) allows the large passive volume to be read-out by a similar number of electronic channels to the Fermi instrument ($\sim$800,000). This approach also allows for a doubling of the number of tracker layers compared with Fermi, and effectively eliminates gaps or embedded electronics in the detector volume. A $3 \times 6\text{m}^2$ instrument would fit inside the shroud of a number of existing launch vehicles. With 3 to 4 radiation lengths of CsI, the instrument and would fit within the mass budget of a heavy lift launch vehicle for a low earth orbit or even a Lagrange-point orbit. Either orbit would limit the total radiation exposure of the fibers to acceptable levels for a 10 year mission, but only the higher orbit would allow the realization of the full potential of the very wide field-of-view. The instrument would achieve an effective area of $\sim 10\text{m}^2$ and an etendu (or geometry factor) (in a high orbit) of 60m^2sr. Based on a rough preliminary cost estimate, the proposed instrument could fit in the budget of a probe-class mission. Such a mission, optimized to address a central scientific question (the nature of dark matter) and addressing critical secondary science (the nature of short GRBs or gravity wave sources) could warrant prioritization in the next decadal survey.

References

[1] M. Ackermann, et al., *Searching for Dark Matter Annihilation from Milky Way Dwarf Spheroidal Galaxies with Six Years of Fermi Large Area Telescope Data*, PRL, **115**, 231301 (2015)

[2] B.P. Abbott, et al., *Observation of Gravitational Waves from a Binary Black Hole Merger*, PRL, **116**, 061102 (2016)

[3] S.P. Wakely, *Precision X-ray transition radiation detection*, Astroparticle Physics, bf 18, 67 (2002)

[4] M. Cherry and G. Case, *Compton scattered transition radiation from very high energy particle*, Astroparticle Physics, **18**, 629 (2003)

The Large Observatory For X-ray Timing Probe (LOFT-P): A NASA Probe-Class Mission Concept

Colleen A. Wilson-Hodge[1] (NASA/MSFC), Paul S. Ray (NRL), Deepto Chakrabarty (MIT), Thomas J. Maccarone (TTU), Marco Feroci (INAF-IAPS) on behalf of the US-LOFT SWG and the LOFT consortium.

LOFT-P is a probe-class X-ray observatory designed to work in the 2–30 keV band with huge collecting area (> 10× NASA's highly successful *RXTE*) and good spectral resolution (<260 eV). It is optimized for the study of matter in the most extreme conditions found in the Universe and addresses several key science areas including:

- Probing the behavior of matter spiraling into black holes (BHs) to explore the effects of strong gravity and measure the masses and spins of BHs.
- Using multiple neutron stars (NSs) to measure the ultradense matter equation of state over an extended range.
- Continuously surveying the dynamic X-ray sky with a large duty cycle and high time-resolution to characterize the behavior of X-ray sources over a vast range of time scales.
- Enabling multiwavelength and multi-messenger study of the dynamic sky through cross-correlation with high-cadence time-domain surveys in the optical and radio (LSST, LOFAR, SKA pathfinders) and with gravitational wave interferometers like LIGO and VIRGO.

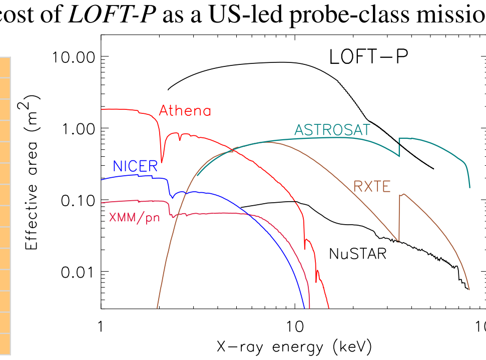
Detailed simulations[2] have demonstrated that an order of magnitude larger collecting area than *RXTE* (i.e., >6 m^2) is required to meet these BH and NS objectives, and a previous engineering study[3] has shown that such an instrument is too large for the Explorer (EX) class and instead requires a probe-class mission.

LOFT-P is adapted from a mission concept that has been under study in both the Europe and the US since 2010 [1]. It comprises two instruments. The Large Area Detector (LAD) consists of collimated arrays of silicon drift detectors (SDDs) with a 1-degree field of view and a baseline peak effective area of 10 m^2 at 8 keV, optimized for submillisecond timing and spectroscopy of NSs and BHs. The sensitive Wide Field Monitor (WFM) is a 2–50 keV coded-mask imager (also using SDDs) that acts as a trigger for pointed LAD observations of X-ray transients and also provides nearly continuous imaging of the X-ray sky with a large instantaneous field of view. The baseline mission specifications are shown in the table below, along with a figure comparing the LAD effective area to other missions.

The technical readiness underlying the *LOFT-P* concept is already high. *LOFT-P* uses large-area SDD technology originally developed for the ALICE-D4 experiment on the CERN Large Hadron Collider. The lead-glass collimators are well studied, with commercial manufacturing capability in Europe (Photonis), Japan (Hamamatsu), and the US.

Cost estimate. Based on the detailed 32-month Assessment Phase (Phase A) study of M-class *LOFT* for the ESA M3 competition in 2013, we estimate a US probe-class mission cost for *LOFT-P* of $770M, incorporating full lifecycle costs including labor, instruments, spacecraft, launch and 3 years of operations. In May 2016 the Advanced Concepts Office at NASA MSFC will perform a preliminary study to verify the cost of *LOFT-P* as a US-led probe-class mission.

Parameter	LAD	WFM
Detector Type	Silicon Drift Detector	Silicon Drift Detector
Number of Units	140 Modules x 16 Detectors/Module	5 Units x 2 Cameras/Unit
Effective Area	10 m^2 (at 8 keV)	364 cm^2 per Unit
Mask	—	0.25 x 14 mm elements (25% open)
Energy Range	2–30 keV (30–80 extended)	2–50 keV (50–80 extended)
Energy Resolution	<260 eV (<200 eV single-anode events)	<500 eV @ 6 keV
Spatial Resolution	—	5 arcmin x 5 arcmin
Field of View	1°	>4 sr (at >20% effective area)
Background	1000–3000 cts/s	550 cts/s per Unit
Time Resolution	10 μs	10 μs (event-mode)
Typical Data Rate (w/compression)	200/1000 kbps (100/500 mCrab)	425 kbps (event mode)
Mass (CBE w/contingency)	1300 kg	130 kg
Power (CBE w/contingency)	1100 W	100 W



Strong gravity and black hole spin. Unlike the small perturbations of Newtonian gravity found in the weak-field regime of general relativity (GR), strong-field gravity results in gross deviations from Newtonian physics and qualitatively new behavior for motion near compact objects, including the existence of event horizons and an innermost stable circular orbit (ISCO). *LOFT-P* observations will probe strong gravitational fields of NSs and BHs in a way that is complementary to gravitational wave interferometers like LIGO and VIRGO. Accretion flows and the X-ray photons they emit are "test particles" that probe the stationary spacetimes of compact objects, whereas gravitational waves carry information about the dynamical evolution of these spacetimes. As a result, *LOFT-P* observations will allow mapping the stationary spacetimes of black holes and testing the no-hair theorem [2]. In GR, only two parameters

[1] colleen.wilson@nasa.gov
[2] http://sci.esa.int/jump.cfm?oid=53447
[3] http://pcos.gsfc.nasa.gov/studies/rfi/Ray-Paul-AXTAR-RFI.pdf

(mass and spin) are required to completely describe an astrophysical BH, and the X-rays originating in the strong gravity regions necessarily encode information about these fundamental parameters.

LOFT-P observations of accreting stellar-mass BHs will be unique in providing three independent measurements of each BH spin from high-frequency quasi-periodic oscillations (HFQPOs), relativistic reflection modelling of Fe (and other) lines, and disk continuum spectra, each using techniques with differing systematic uncertainties. In those systems in which HFQPOs have already been detected with $\sim 5\%$ rms amplitude by *RXTE*, deeper observations with *LOFT-P* will allow detections of the 5–10 additional QPO peaks predicted by theory. This will identify their frequencies with particular linear or resonant accretion disk modes; this will be possible once a spectrum of modes is observed, instead of just a pair. *LOFT-P*'s timing capabilities can also test whether the correct spins have been obtained by reverberation mapping of the X-ray reflection in X-ray binaries and AGN (with better S/N than *Athena*).

Properties of ultradense matter. How does matter behave at the very highest densities? This seemingly simple question has profound consequences for quantum chromodynamics and for compact object astrophysics. The equation of state (EOS) of ultradense matter (which relates density and pressure) is still poorly known, and exotic new states of matter such as deconfined quarks or color superconducting phases may emerge at the very high densities that occur in NS interiors. This regime of supranuclear density but low temperature is inaccessible to laboratory experiments (where high densities can only be reached in very energetic heavy ion collisions), but its properties are reflected in the mass-radius (M-R) relation of NSs. Consequently, measurement of NS M and R is the crucial ingredient for determining the ultradense matter EOS.

LOFT-P will obtain M and R measurements by fitting energy-resolved oscillation models to the millisecond X-ray pulsations arising in a hot spot from rotating, accreting NSs. The detailed pulse shape is distorted by gravitational self-lensing, relativistic Doppler shifts, and beaming in a manner which encodes M and R. Detailed modeling of the pulse profile can extract M and R separately [3]. Measurements of both M and R for three or more NSs, made with $\approx$5% precision, would definitively determine the EOS of ultradense matter, while measurement of a larger number of NSs with $<$10% precision would still place strong constraints. The recently approved *NICER* mission will apply this same technique to faint rotation-powered pulsars, a different class of NSs. This is complementary to *LOFT-P* rather than duplicative. A key difference between the NSs targeted by *NICER* and *LOFT-P* is that the *NICER* targets generally rotate more slowly ($<$300 Hz) than the *LOFT-P* targets ($>$600 Hz). As a result, *NICER* observations cannot fully exploit Doppler effects to break degeneracies between M and R, making precise and uncorrelated measurements more difficult. *NICER* will obtain precise ($<$5%) determinations of R for only 1–2 sources; this is unlikely to be sufficient to solve the EOS problem, since multiple measurements are required to measure the slope of the M-R curve and, hence, of the pressure-density relation that describes the EOS. Combining M-R measurements from *NICER* and *LOFT-P* will triple the sample size.

The M-R relation of neutron stars can also be probed with magnetar oscillations. Like with the HFQPOs, by dramatically improving the collecting area, enough frequencies should be found to allow mode identification. Given the relative precision of timing calibration to response matrix calibration, timing-based models should eventually allow the highest precision measurements possible.

Observatory science As a flexible observatory with superb spectral-timing capabilities and wide field coverage of the sky over a broad range of timescales, *LOFT-P* will serve a large user community and make significant scientific impact on many topics in astrophysics. The LAD will study accretion physics, jet dynamics (especially in conjunction with timing studies in the infrared that will be possible on medium-sized telescopes), and disk winds (taking advantage of the high throughput and high spectral resolution which will allow very rapid detection of the turn-on of a disk wind).

The WFM's combination of angular resolution, sensitivity, spectral resolution and *instantaneous* wide-field coverage will enable studies of black hole transients, tidal disruption events, and gamma-ray bursts too faint for current instrumentation. It will also enable instant spectroscopic follow-up of these events, as the positional accuracy will be smaller than the fields of view of modern integral field units. The WFM's mission-long survey of the sky in Fe Kα will be more sensitive to Compton thick AGN than *eROSITA*.

The WFM will be unique as a discovery machine for the earliest stages of supernova shock breakouts by working in the X-rays, and having the sensitivity and instantaneous field of view to have an expected detection rate of a few breakouts per year within 20 Mpc. This will allow much more rapid spectroscopic follow-up than other means of discovering supernovae, allowing crucial studies of the early stages of the explosions that can be used to probe details of the explosion mechanisms and the binarity of supernova progenitors. *LOFT-P* will be ideal for detecting and localizing X-ray counterparts to gravitational wave sources, fast radio bursts, and optical transients in the era of LSST.

References. [1] Feroci, M. et al. 2014, Proc. SPIE 9144, 91442T; [2] Psaltis, D. 2008, Liv. Rev. Rel., 11, 9; [3] Watts et al. 2016, Rev. Mod. Phys., in press (arXiv:1602.01801)

For more information see:
`https://sites.google.com/site/loftpmissionpage/`

Death of Massive Stars (DoMaS) Probe

Pete Roming* (proming@swri.edu), Eric Schlegel†, Thomas Greathouse*, Neil Gehrels*,
Chris Fryer+, Derek Fox◆, Michael Davis*, Amanda Bayless*

I. INTRODUCTION

The death of massive stars is a fundamental process in the shaping of the Universe. The first massive stars are considered a significant contributor to reionization and the dispersal of the first metals. These first stars also form the seeds for the formation of supermassive black holes (e.g. 1-2). Later generations continue the production and dissemination of heavy elements, which shape planets, solar systems, future generation of stars, and galaxies. They form the neutron stars and black holes in the universe, dictating the characteristics and formation rates of X-ray binaries, X-ray bursts and gravitational wave sources (e.g. 3-5). Despite their importance, the nature of the first stars, when and how they reionized the Universe, and how massive stars end their lives, is not well understood. An astrophysics probe-class mission with greatly expanded capabilities, such as DoMaS, will readily address these problems.

II. SCIENCE DRIVERS

Massive stars end their lives as gamma-ray bursts (GRBs) and supernovae (SNe). Because of their extreme luminosities, GRBs are excellent probes for addressing the nature of the first stars and when and how they contributed to reionization, while the shock breakout (SBO) of SNe is one the best tools for ascertaining the nature and death of massive star progenitors.

2.1. Nature of the First Stars and Their Contribution to Reionization

The first stars are arguably massive (e.g. 6) and some will end their lives as GRBs (e.g. 7). Sufficiently high signal-to-noise (S/N) spectra of the corresponding afterglows will deliver measurements of the HI fraction in the IGM at the redshift of the bursts (i.e. 8). These afterglows will be exceptionally valuable targets for such studies, as they have featureless, synchrotron power-law spectra, permitting straightforward identification of the absorption signatures, thus uncovering the metallicity and ionization states in their host galaxy. These spectra will reveal the history of reionization, including variations along multiple sight lines; the escape fraction of ionizing radiation from high-z star forming regions, an important variable in reionization models; and the processes of metal enrichment in the early Universe.

2.2. Nature and Death of Massive Star Progenitors

The first electromagnetic signature in the death of massive stars is the SN SBO, which is strongly manifested in the soft X-ray and EUV regimes (e.g. 9-10; Fig. 1). High S/N spectra within seconds to minutes after the SBO event will uncover the true nature of the physics behind these events, an area that is still poorly understood. The properties of the SBO – such as temperature, energy, and photon diffusion time (11) – provide a powerful way of exploring the photosphere of the star and constraining the SN progenitor. These spectra are superb probes of: stellar radii, which are key in eliminating major uncertainties in binary population synthesis models (e.g. distinguishing between compact mergers being black holes and double neutron star systems - important for LIGO); stellar mass-loss that reveal the quantity of mass lost for different stars, ultimately determining the remnant mass distribution; and stellar mixing, crucial for removing major uncertainty in stellar evolution and SNe, including nucleosynthesis and galactic chemical evolution. Detection of SBOs also provides an alert to observers of a new SN immediately after core collapse.

2.3. Ancillary Targets

Although not drivers of observatory requirements, due to the survey nature of the previous two science cases, important astrophysical targets of various kinds will also be observed. These include lower redshift sub-luminous, short, and long GRBs; thermonuclear bursts; flare stars; SNe Ia breakouts; superfast X-ray transients; classical novae; tidal disruption events; blazars; AGNs; soft γ-ray repeater flares; and hot OB stars with winds, to name a few.

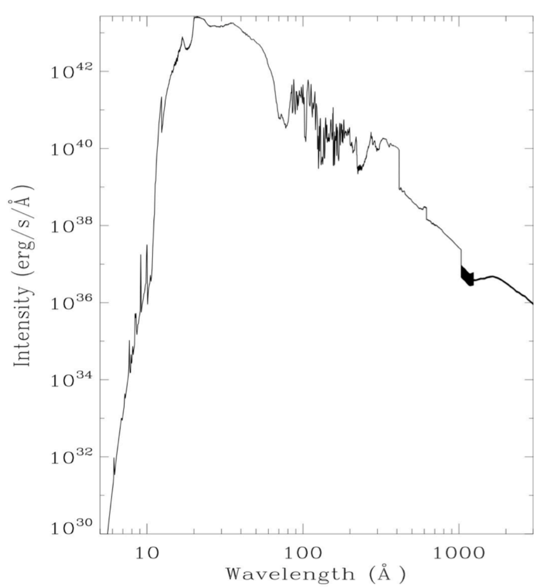


Fig 1. SBO model for a core-collapse SN. Peak flux is found in the soft X-ray and EUV regions.

*Southwest Research Institute; †University of Texas, San Antonio; *NASA Goddard Space Flight Center; +Los Alamos National Lab; ◆Pennsylvania State University

III. TECHNICAL CAPABILITIES

To address the first science problem, DoMaS requires GRB detection and afterglow instruments that are particularly sensitive to high-*z* GRBs. For GRB detections at high-*z*, the optimal instrument is a wide-field soft X-ray telescope (WFSXT) rather than one tuned for the harder X-ray or gamma-rays (cf. 12). Using the new and exciting Lobster-eye technology, such an instrument can achieve sensitivities that are 100 times better than current coded apertures (13). Afterglow follow-up requires a large aperture (~1m) narrow-field near-IR telescope (NIRT) capable of medium resolution slit spectroscopy in order to capture the afterglow at its brightest and maximize the spectral S/N. Based on a fluence of $\sim 10^{-9}$ erg cm^{-2} and field-of-view (FoV) for the WFSXT, convolved with models of high-*z* GRBs based on *Swift*, *Fermi*, and CGRO data (14), DoMaS would detect ~350 $z>8$ GRBs and ~30 $z>12$ in a 5-year mission.

Tackling the second science question necessitates detection and follow-up spectroscopy of SNe SBO events. As with GRBs, because of their paucity, detecting breakout events requires a wide FoV instrument such as WFSXT. For follow-up spectroscopy, a medium aperture (~50cm) narrow-field far-UV telescope (FUVT) capable of medium resolution slit spectroscopy is required for capturing strong key diagnostic lines. Based on the FoV of the WFSXT and the core-collapse SNe rate (e.g. 15), DoMaS would detect ~400 SBO events out to 100 Mpc in a 5-year mission.

A near-geostationary orbit with telescopes pointed anti-sun is ideally suited for this observatory. The WFSXT will continuously monitor the sky for GRB and SBO events, while the narrow-field instruments observe formerly triggered events or ancillary science targets. When the WFSXT triggers an event, the spacecraft rapidly (~0.5°/s) slews to the target allowing the co-aligned narrow-field instruments to begin immediate observations. Public rapid notifications of the target location, brightness, and redshift are sent through TDRSS to ground-based observers. Key instrument parameters are provided in Table 1. The total cost for the observatory, based on cost models (MICM, NICM, PCEC), is $762M in FY16 dollars.

Table 1. Key Instrument Parameters

Telescope	Energy/ Wavelength	Angular Resolution	FoV	Resolving Power (R)	Sensitivity
WFSXT	0.2-5.0 keV	1 arcmin	2.4 sr	40	1.6×10^{-11} erg cm^{-2} s^{-1}
NIRT	0.7-2.5 µm	1 arcsec	30 arcmin	1000	3.9×10^{-20} erg cm^{-2} s^{-1} $Å^{-1}$ @ 1.6 µm in 1 s
FUVT	130-300 nm	1 arcsec	30 arcmin	1000	2.4×10^{-17} erg cm^{-2} s^{-1} $Å^{-1}$ @ 1700 Å in 1 s

IV. NEW TECHNOLOGIES

With the exception of a GaN microchannel plate (MCP), all technologies are TRL 6 or higher. The GaN MCP is at TRL 4 and is estimated to be at TRL 6 or higher within a 5-year period.

V. PROBE-CLASS MISSION NEED

Because of the rarity of high-*z* GRBs, a steradian-level FoV is required for the WFSXT. A MIDEX-class mission is not capable of accommodating the required number of WFSXT modules to achieve such a FoV. Rapid high S/N spectroscopic follow-up requires an ~1m NIRT which also cannot be accommodated on a MIDEX. The high-z GRB science objectives are readily met within a probe-class mission.

Simulations show that SBO physics is much more complex than the simple semi-analytic models predict, while full transport calculations reveal that the details of the explosion can also alter the SBO. A high event rate (which can't be done with a MIDEX for the same reason as GRBs), but reasonable narrow-field follow-up is needed to constrain the explosion parameters and extract information about the stars from the observations.

REFERENCES

[1]Johnson, J., et al. 2012, ApJ, 750, 66; [2]Whalen, D., & Fryer, C. 2012, ApJ, 756, L19; [3]Fryer, C., Woosley, S., & Hartmann, D. 1999, ApJ, 526, 152; [4]Belczynski, K., et al. 2014, ApJ, 789, 120; [5]Dominik, M., et al. 2015, ApJ, 806, 263; [6]Bromm, V. 2013, Rep. Prog. Phys, 76, 112901; [7]Ioka, K., et al. 2012, IAUS, 279, 301; [8]Totani, T., et al. 2006, PASJ, 58, 485; [9]Klein, R., & Chevalier, R., 1978, ApJ, 223, L109; [10]Falk, S. 1978, ApJ, 225, 133; [11]Matzner, C., & McKee, C. 1999, ApJ, 510, 379; [12]Burrows, D., et al., 2012, Mem. S. A. It. Suppl., 21, 59; [13]Gehrels, N., et al. 2012, IAUS, 285, 41; [14]Ghirlanda, G., et al., 2015, MNRAS, 448, 2514; [15]Graur, O., Bianco, F., and Modjaz, M. 2015, MNRAS, 450, 905

Whitepaper on

Transient Astrophysics Probe (TAP)

Jordan Camp (GSFC)
Neil Gehrels (GSFC)

M. Ajello (Clemson), S. Barthelmy (GSFC), M. Bautz (MIT), E. Berger (Harvard), D. Burrows (PSU), N. Butler (ASU), P. Caraveo (INAF, Italy), S.B. Cenko (GSFC), D. Chakrabarty (MIT), R. Chevalier (UVa), C. Dermer (NRL), Abe Falcone (Penn State), S. Gezari (UMd), G. Gonzalez (LSU), C. Fryer (LANL), P. Giommi (ASDC, Italy), P. Gorenstein (CfA, Harvard), J. Grindlay (Harvard), E. Grove (NRL), S. Guiriec (UMd), D. H. Hartmann (Clemson), J. Hill (GSFC), V. Kalogera (Northwestern), C. Kouveliotou (GWU), J. Kruk (GSFC), A. Kutyrev (GSFC), J. Livas (GSFC), H. Moseley (GSFC), C. Miller (UMd), Sergio Molinari (INAF, Italy), R. Mushotzky (UMd), P. O'Brien (Leicester U., UK), Julian Osborne (Leicester U., UK), J. Perkins (GSFC), R. Petre (GSFC), L. Piro (INFN, Italy), A. Ptak (GSFC), J. Racusin (GSFC), R. Remillard (MIT), M. Rieke (U Arizona), A. Sesana (U. Birmingham), J. Schnittman (GSFC), P. Shawhan (UMd), S. Starrfield (Arizona State University), G. Tagliaferri (INAF, Italy), M. Tavani (INAF, Italy), A. J. van der Horst (GWU), R. Willingale (U Leicester), K. Wood (NRL), W.W. Zhang (GSFC)

Transient Astrophysics Probe (TAP) Concept

The recent announcement of a Binary Black Hole merger detected by LIGO has stimulated enormous interest in the possibility of observing electromagnetic counterparts to gravitational wave (GW) sources. The Transient Astrophysics Probe will host a set of X-ray and near IR instruments that will provide an optimal means for EM follow-up and localization of GW detections by the ground-based LIGO as well as the planned space-based GW observatory LISA (assuming launch dates for TAP and LISA late next decade). Counterparts to very massive GW sources identified by Pulsar Timing Arrays may also be detected.

TAP will also revolutionize our knowledge of the time domain universe. It will provide capabilities for a major step forward in high redshift universe and epoch of reionization studies by detecting gamma-ray bursts to redshift $z > 12$, answering questions about the nature of the first stars and chemical evolution. It will provide a bonanza of detections of tidal disruptions and supernova shock break-outs. In its survey mode, TAP will perform a deep and wide survey of the X-ray sky, most notably active galactic nuclei, whose variability determination will allow us to effectively distinguish them from candidates for LISA and PTA GW counterparts. Inspired by the model of Swift, sensitive X-ray and IR rapid follow-up instruments will give valuable information on each detected transient.

To this end, TAP (Figure 1) is a mission concept that combines an X-ray wide-field imager (WFI) with a sensitive X-ray telescope (XRT) and a wide-field IR telescope (IRT). The WFI has a sensitivity of 10^{-11} erg/sec/cm^2 (2000 sec) in a combined 2 sr field of view that covers ~80% of the sky every 3 hr in multiple pointings. It is based on CCD technology and lobster-eye microchannel optics. The XRT (2×10^{-15} erg/sec/cm^2 in 3000 sec) will have a relatively large field of view (1 deg^2) and 5 arc sec resolution, facilitating LISA follow-ups. The IRT has a 40 cm diameter mirror, a wavelength range of 0.6 – 2.4 μm, a 1 deg^2 FoV, and is capable of multiband photometry and $\lambda/\delta\lambda=30$ slit spectroscopy. A rapid response, autonomously pointed spacecraft directs pointing of TAP's instruments.

TAP is then ideally suited for the challenging job of detecting EM counterparts of GW transients. Only the Lobster technology offers a wide enough field of view and high sensitivity needed to cover large error boxes that will still be the norm for LIGO gravitational wave events in the 2020's. The IR and X-ray telescopes will be mainly tasked for WFI follow-up measurements, but will also be available to search for GW counterparts not identified by the WFI. The IR telescope will be a powerful instrument for detection of predicted isotropic kilonova signatures from binary neutron star mergers that GW instruments will detect, with a potentially large increase in rate relative to the (beamed) X-ray afterglow. The sensitive, 1 deg^2 FoV XRT will allow the follow-up of LISA detections of SMBH binary mergers potentially out to z~2. The combination of GW and EM detection will greatly increase the science return from the GW networks of the late 2020's.

Further, the tantalizing glimpses afforded us to date by serendipitous sources such as tidal disruption events, high redshift GRBs and supernova shock break-outs have underscored the necessity of more efficient discovery techniques in order to enhance the future rate of discovery in time domain astronomy. TAP offers enormous advances in capabilities compared to current missions. The WFI is 30 times more sensitive than existing wide-field X-ray monitors. The rapid-response spacecraft and sensitive IR telescope will provide immediate information on the transient's nature and distance. The XRT will employ state-of-the art optic fabrication techniques to offer high sensitivity with unusually large FoV.

Finally, there will be considerable synergy in the time-domain X-ray analysis afforded by TAP with other wavelength time-domain facilities including LSST (optical) and LOFAR and SKA (radio).

The detection rates expected in the late 2020s are impressive:

LIGO GW Counterpart: NS-NS/NS-BH	~monthly	(so far undetected)
LISA GW Counterpart: SMBH-SMBH	~several/yr[1]	(so far undetected)
PTA GW Counterpart: SMBH-SMBH	~10(5 years)[1]	(so far undetected)
GRBs	twice daily	(current rate 2/week)
High-z GRBs (z>7)	bi-monthly	(current rate 1/3yr)
SN shock breakout	weekly	(current rate yearly)
Tidal disruption flares	weekly	(current rate yearly)
Stellar super flares	weekly	(current rate yearly)

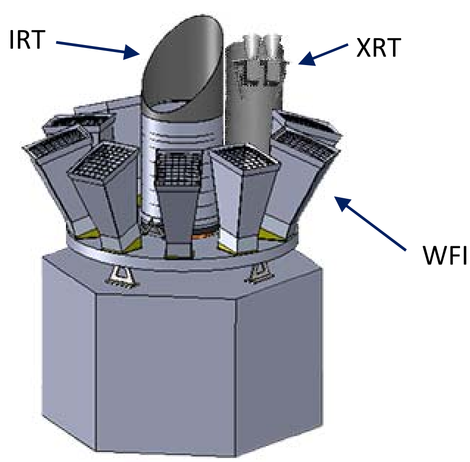


Fig. 1 Schematic of TAP, showing 8 WFI modules, IRT (center), and XRT

The cost of TAP was estimated from experience at Goddard in generating cost estimates for the (independently reviewed) 2010 Lobster free-flyer mission proposal, and from Goddard MDL runs in 2010 and 2015. To the $200M Lobster cost, we added inflation, 5 more Lobster modules, the XRT, and a launch vehicle, bringing the total cost to ~$750M. All technologies are TRL 6 or higher, with no technology development needed.

[1] Private communication, A. Sesana

The Time-domain Spectroscopic Observatory (TSO)

White Paper for an Astrophysics *Probe-Class* Mission Concept

P.I. Prof. Jonathan Grindlay
Harvard University, Center for Astrophysics, josh@cfa.harvard.edu , 617-495-7204

Co-I's: E. Berger, G. Djorgovski, N. Gehrels, P. Green, F. Harrison, D. Hartmann, S. Kahn, A. Kutyrev, B. Metzger, G. Melnick, H. Moseley, B. Peterson, G. Rieke, N. Tanvir, T. Tyson, & Z. Ivezic

Summary: A *Time-domain Spectroscopic Observatory (TSO)*, enabled by a 1.5m OIR (0.4-5μm) telescope in Geosynch orbit above *LSST*, will reveal the time-domain astrophysics from the deluge of *LSST* transients and current and future wide-field surveys. Of particular importance to Astro2010 and (likely) Astro2020 objectives, TSO would provide the sensitivity and rapid response to at long last identify optically "dark" long GRBs at z > 6 as probes of the rates of star formation and growth of structure during the entire Epoch of Reionization (EOR, z ~6 – 20) in response to GRB triggers from current and future imaging GRB missions. By providing near simultaneous spectroscopy with nightly *LSST* survey measures of AGN flares on enormous samples of AGN out to z ~7, *TSO/LSST* will measure the SMBH *M-sigma* relation and growth of SMBH masses over cosmic time. *TSO* enables low-cost continuous data/commanding and ≥TRL-6 telescope/instrument systems at known cost.

Spectroscopy is the key to the physical understanding of astrophysical systems. The *Time-domain Spectroscopic Observatory (TSO)* would serve the rapidly growing field of Time Domain Astrophysics (TDA), for which time-critical spectroscopy is needed for fields from Exoplanets and Galactic black holes to cosmologically distant GRBs. A dedicated imaging and spectroscopy telescope that can provide continuous and/or immediate response must be in space, where the sensitivity increase (per unit area telescope aperture) is particularly significant in the ~0.8 – 2.2μm band by the lack of OH airglow backgrounds and the sensitivity gains by modest radiative cooling of the telescope. *Spectroscopy (R = 5) for a 1.5m TSO is ~10X more sensitive than imaging (R =1) in the J,H,K bands is for the 8.4m Subaru telescope* (Fig. 1) or VLT. Key *TSO* telescope, instrument and mission parameters and heritage are given in Table 1. The focal plane and detector design is based on the extensive studies (Kutyrev+2010) for *EXIST* for Astro2010. Design studies were also done for the radiative cooling of the optical bench and 1.1m IRT proposed for *EXIST*. The *TSO* mission operations design is particularly advantageous, given the continuous LOS data/commanding link that would be available to White Sands from the *LSST*-longitude Geosync orbit. Mission operations for this purely point-and-stare mission include semi-autonomous target

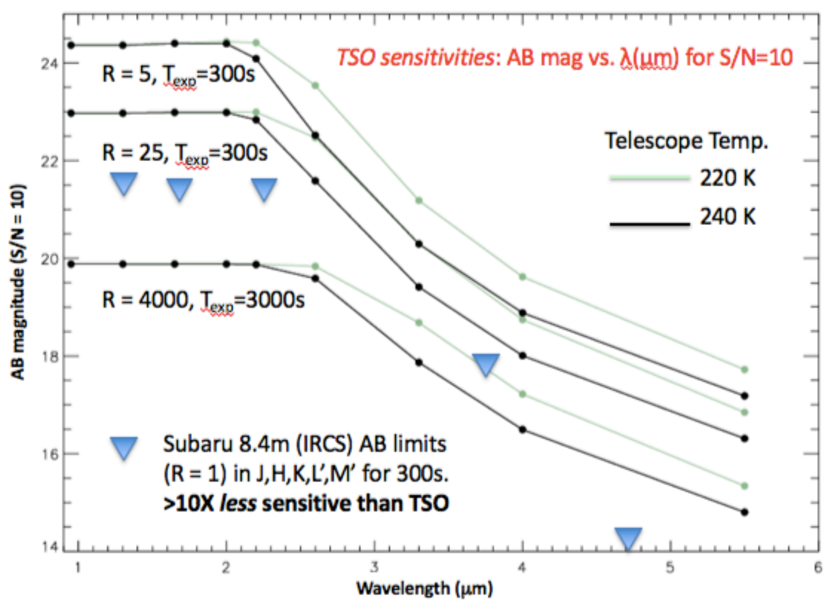


Figure 1. *TSO* sensitivity (S/N=10) vs. resolution R and Texp.

Table 1. Parameter	*TSO*	Heritage
Spectral range	0.4 – 5μm	*JWST*/NIRSPEC
Spectral resolution	R = 5, 25, 4000	*EXIST*/IRT study
Imaging detector	H2RG/HyViSi arrays	NIRSPEC
FoV; pixel resolution	5 x 5arcmin; 0.15arcsec	NIRSPEC
Telescope; rapid slew	1.5m R-C, rad.cooled -50C	*Swift, JWST*
Orbit	Geosync.; over *LSST*	Commercial

selections from real-time *LSST, Swift, LIGO…* triggers and pre-planned targets. Our estimated total mission cost, including a Falcon 9 launch, 5y of operations and a Guest Observer program, is $650M. The telescope would use a light-weighted Schott Zerodur "space mirror", and the focal plane imager-spectrograph and rapid-slew spacecraft (for GRBs) are well understood (Table 1). Major *TSO* science objectives include:

Measuring the Growth of Structure and Star Formation Rate in the EOR. Only ~30% of *Swift* GRBs have redshifts due to the inadequacy of ground-based rapid response spectroscopy and nIR sensitivity. The highest spectroscopic redshift GRB at z = 8.2 (Tanvir+2009) was recorded (R = 500) with VLT/ISAAC ~17h after the burst with marginal S/N. This same event could be measured at 8h (if Earth blocked) by *TSO* with R = 4000 at z = 15. With a conservative 90% redshift yield from *TSO*, the *Swift* 10y sample of 5 GRBs at z >6 would be ~20, including the ~22% contribution of "dark" bursts at z >5 (Greiner+2011). With a future 4π sr imaging X-ray (and GRB) SMEX mission instead of the 1.5sr FoV of *Swift/BAT*, the total would be ~200, or ~20/year. These numbers increase to >30/year if GRB imagers with sensitivity 3-200 keV provide the GRB triggers. Over its 5y mission, *TSO* can then measure the damped Lyα profiles of ~150 GRB host galaxies at z >6 with R = 4000 spectroscopy to measure the neutral vs. ionized H fraction in the host galaxy vs. local IGM and thus trace the EOR vs. z, as proposed by McQuinn+2008. Just as exciting, the distribution of GRBs vs. z would measure the star formation rate SFR(z) for z ~6-15. Even *JWST* cannot trace supernovae, or galaxies, over most of this range.

Measuring the Growth of Supermassive Black Holes over z = 0 - 7: The intended synergy with *LSST* allows *TSO* to make another fundamental contribution: measure the supermassive black hole (SMBH) mass spectrum over z = 0 – 7. This is enabled by the *essential* spectroscopic capability to continuously track and measure AGN spectra of a large (>$10^{3\text{-}4}$) sample and derive SMBH masses by reverberation mapping (Peterson 2014) of AGN flaring by timing the response of the broad line region (BLR) spectrum and line widths (*TSO*) to optical flaring from the central SMBH (*LSST*). *LSST* with its ~3day cadence to return to a given patch of sky for ~8months over its 10y lifetime, will measure truly enormous samples of AGN and their flares. All classes, from Seyfert II's to luminous FSRQs (with BLRs) are included so that SMBH mass vs. host morphology and SFR can be separately studied vs. z. *TSO* absorption line spectra beyond 1μm will constrain galaxy masses and metallicities where the AGN continuum falls off. Even Compton-thick AGN can be measured (*TSO* Br-γ vs. z,y *LSST* magnitudes).

Discovering EM counterparts to *ALIGO* NS-NS and NS-BH mergers: In the era of *TSO*, the *ALIGO, AVIRGO,* and *KAGRA* gravitational wave telescopes will detect many BH-BH mergers (GW150914) and neutron star (NS) mergers with NSs and BHs. NS mergers produce SGRBs and kilonovae with optical/IR signatures (Metzger and Berger 2012) as likely detected just after SGRB130603B. In response to a *ALIGO-AVIRGO* (at least) trigger, *LSST* could do a ~3-5h raster imaging search of the ~30-100 deg^2 gravitational wave error box and find the predicted (more rapid decay in blue than red than IR; Kasen+2015) lightcurves arising from a lanthanide-rich disk wind of neutronized material ejected from the merger. *TSO* spectra would measure wind velocities and composition to probe the merger physics, NS equation of state, and constrain the progenitor system as NS-NS vs. NS-BH.

From exoplanets to stellar black holes and tidal disruption in galactic nuclei: With the *TSO* sensitivity and thus speed ~10X that of Keck or VLT at ~1 - 5μm, there are numerous new opportunities. *Exoplanets* in habitable zones around M dwarfs can have their transit spectra stacked to search for H_2O (1-4μm) and CO_2 (1.5-4.5μm) absorption features, and debris disk spectral variability probes terrestrial planet building. *SgrA* flares and quiescent BH-LMXBs vs. magnetic CVs* producing the "diffuse" hard X-ray emission in the Galactic Center region (Perez+2015) can be distinguished with *TSO* spectra, as can *Tidal Disruption Events vs. SNe* in obscured galactic nuclei. If a detailed design study shows the rapid-slew *TSO* telescope can be cooled to ~150K rather than the (conservative) 220K or 240K shown in Fig. 1, the AB sensitivities at 2μm extend flat to 5μm. MgII in galaxies is then detectable for GRB afterglows at z = 15, and Hβ line widths for SMBH masses at z = 9.

References: Greiner+2011, A&A, 526, A30; Kasen+2015, MNRAS, 450, 1777; Kutyrev+2010, Proc. SPIE, vol. 7731, 77311Z; McQuinn+2008, MNRAS, 388, 1101; Metzger & Berger 2012, ApJ, 746, 48; Peterson 2014, Sp.Sci.Rev., 183, 275; Perez+2015, Nature, 520, 646; Tanvir+2009, Nature, 461, 1254

Title: GreatOWL, a space-based mission to realize charged-particle and neutrino astronomy

Authors: John Mitchell & John Krizmanic (NASA/GSFC) & Douglas Bergman (Utah)
Email Contacts: John.W.Mitchell@nasa.gov, John.F.Krizmanic@nasa.gov

Science Drivers: The sources of the most energetic particles in the Universe, the Ultra-High Energy Cosmic Rays (UHECRs), still remain a mystery. What object(s) can accelerate a particle to > 10^{20} eV? This is more than a factor of 10^7 times the energy of a 7 TeV LHC beam. What is the nature of the acceleration mechanism? What is the composition of this radiation and how does it evolve at the highest energies? What is the flux of UHE neutrinos? The acute need for measurements to address these questions has been explicitly described in the past two NAS Decadal Surveys of Astronomy and Astrophysics [1,2], and "How do Cosmic Accelerators Work and What are They Accelerating?" was one of the top eleven science questions for the 21st century listed in the Turner Report [3]. The uncertainty in the nature of UHECRs and their sources still remain even with about a decade of operation of each of the largest ground-based UHECR experiments, the Pierre Auger Observatory (PAO) and the Telescope Array (TA). Based upon the results of these ground-based experiments, the existence of the Greisen-Zatsepin-Kuzmin (GZK) suppression above 4 $\times 10^{19}$ eV suggests that most UHECR originate in astrophysical objects. Higher energy particles must come from sources within about 100 Mpc and are deflected by ~1 degree by predicted intergalactic/galactic magnetic fields. While PAO [4] and TA [5] have reported areas of ~3 σ excess of events in the southern and northern hemispheres respectively, the sources remain unresolved. Thus the potential for charged-particle astronomy and UHE neutrino astronomy (using GZK neutrinos) exist, but only if an experiment has the exposure (in a reasonable time frame) to overcome the paltry overall UHECR rate of ~ 1 event per km^2 century above ~$10^{19.5}$ eV. Space-based UHECR experiments provide a mechanism to overcome the exposure limitations of ground-based experiments and can survey both the northern and southern skies. Around 2000, the free-flying Orbiting Wide-angle Light Collectors (OWL) mission (see Figure 1) [6] and the ISS-based Extreme Universe Space Observatory (EUSO) [7] were designed to obtain the needed, large exposure on a few year timescale and to operate above $10^{19.5}$ eV. EUSO has evolved into JEM-EUSO [8], which will be the pathfinder experiment demonstrating the technique of space-based UHECR measurements. Here we discuss the GreatOWL mission [9], which is based upon OWL but with significantly improved performance to perform charge-particle astronomy, to determine the nuclear composition evolution of UHECR above 10^{19} eV, and to have enough exposure to measure the flux of GZK-induced neutrinos. Specifically, GreatOWL will have the following UHECR and UHE neutrino science reach:

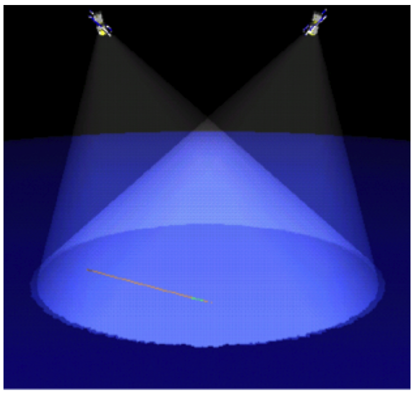


Figure 1: The OWL concept: two 'eyes' stereoscopically viewing an extended air shower from low-Earth orbit. The FOV and common atmospheric volume are highlighted.

- With the GreatOWL 'eyes' in 3300 km orbits, in 5 years with 10% duty cycle the exposure will be ~10^7 km^2 sr yr (~290 times the exposure for Auger in 5 years) for UHECR above 10^{19} eV with an angular resolution of ~1 deg and with ~20% energy resolution.
- With the GreatOWL 'eyes' in 1000 km orbits, in 5 years with 10% duty cycle the exposure will be ~10^6 km^2 sr yr for UHECR above 10^{18} eV, will have the sensitivity to measure ~40 GZK neutrino events/yr, and will be able to measure the nuclear composition evolution of UHECR above 10^{19} eV.

Technical Capabilities: Figure 1 illustrates the original OWL concept: two orbiting near-UV (330 – 400 nm) imaging telescopes, flying in a loose formation in 1000 km orbits, stereoscopically measure the nitrogen fluorescence signal during moonless nights from Extended Air Showers (EAS) induced by UHECRs interacting in the Earth's atmosphere. The co-measurement allows for a straightforward reconstruction of the incidence direction, distance from the EAS to each instrument, and provides a cross-check of the measurement of the EAS profile, required to measure the energy and identity of the UHECR primary particle, in order to miminize the effects of atmospheric variability. Each OWL 'eye' is an f/1 Schmidt camera with a 45° full FOV and the highly-pixelated focal plane samples the near-UV signal at 10 MHz. The optical performance is quite modest, the optical angular needed is ~1 milli-radian, over 10^4

away from the diffraction limit. Thus each OWL 'eye' is more like a 'light bucket' with performance requirements closer to a microwave dish. An illustration of a deployed OWL 'eye' is shown in Figure 2.

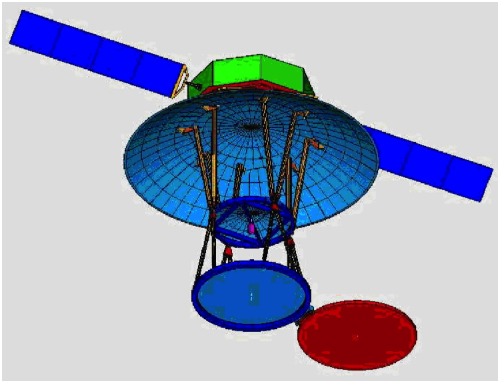


Figure 2: A Fully deployed OWL instrument with the light shield removed for clarity.

GreatOWL extends the performance of OWL by increasing the UV light-collection capability by a factor of 70 to yield a full aperture energy threshold of 10^{18} eV for a configuration with the GreatOWL 'eyes' in a 1000 km orbits, while another configuration using 3300 km orbits increasing the exposure by ×10 assuming for the same time span of operation. The increase in light collection is based on incorporating UV sensitive SiPMs as the focal plane detector and scaling the optics by ×6. This leads to a GreatOWL instrument with a 42 m diameter mirror, an 18 m diameter optical aperture, and a 13.8 m diameter focal plane array. This would be prohibitively massive and complex using conventional, rigid structures such what was assumed for the original OWL. However, rigidized inflatable structures could form the mirror and other structures a relatively lightweight spacecraft with a relatively lightweight and compact stowed design, allowing for easier launch vehicle accommodation. In 1996, the Space Shuttle mission STS-77 deployed the 14 m diameter Inflatable Antenna Experiment, and a picture of the deployed antenna is shown in Figure 3. Since then there has been progress on developing inflatable structures, such as that used in the Spartan 208 Shooting Star telescope and the Bigelow Expandable Activity Module (BEAM) that will be launched to the ISS in 2016. The technology development needed for GreatOWL would leverage off of these.

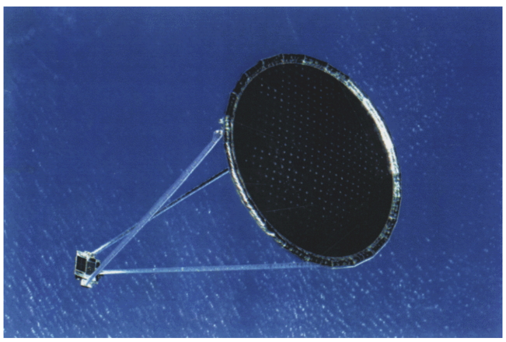


Figure 3: NASA's deployed 14 m diameter Inflatable Antenna Experiment (IAE).

New Technologies: Significant/5 years. R&D is needed to develop the inflatable optics and structures, a foldable large-area focal plane array, and mechanical engineering to assemble these into a spacecraft in a stowed then deployed configuration.

Reasons why a probe-class mission is needed: A 2002 GSFC ISAL & MSAL runs developed the OWL baseline instrument and mission designs and determined a mission cost to be $360 M (not including launch vehicle). Like OWL, GreatOWL requires two instruments and a dual-manifest launch. Assuming 3% yearly inflation, the FY2016 cost places this above the cost-cap for a MIDEX.

Cost Estimate: Based on inflating 2002 OWL mission cost by 3% inflation, this yields a mission cost estimate of $540 M, not include the launch vehicle.

References:

1. *Astronomy and astrophysics in the new millennium*, National Academies Press (2001).
2. *Panel reports–new worlds, new horizons in astronomy and astrophysics*, National Academies Press (2011).
3. *Connecting quarks with the cosmos: Eleven science questions for the new century*, National Academies Press (2003).
4. Aab, A. et al., ApJ 804, id 15 (2015).
5. Abbassi, R.U. et al., ApJ 790, id L21 (2014).
6. Stecker, F.W. et al., Nucl. Phys. B 136, 433–438 (2004).
7. EUSO Collaboration, Nucl. Phys. B 136, 415–432 (2004).
8. Ebisuzaki, T. et al., Advances in Space Research, 53, 1490-1505 (2014).
9. Krizmanic, J.F. et al., Proc. 33rd ICRC (Rio de Janeiro), Paper 1085, arXiv:1307.3907 (2013).

The Inflation Probe: A Probe-Class Astrophysics Mission[1]

SCIENCE DRIVERS: The Cosmic Microwave Background (CMB) radiation consists of a bath of photons emitted nearly 14 billion years ago, when the universe was in its infancy. Inflation models predict a stochastic background of gravitational waves should leave a faint polarized signal in the CMB, which can be detected and characterized with modern polarization-sensitive instruments. A convincing detection of the resulting distinctive "B-mode" signature would provide a measure of the amplitude of gravitational waves emitted during a primordial inflationary epoch [2,3]. Such a detection and spectral characterization would confirm the inflationary paradigm and identify the energy scale at which inflation took place, revealing fundamental physics at energy scales impossible to achieve in any terrestrial laboratory. In addition, a cosmic-variance limited measurement of the entire sky over a wide range of frequencies and angular scales will enable the use of CMB lensing as a probe of large scale structure; provide a definitive determination of the epoch of reionization; characterize astronomical foregrounds; measure neutrino masses; and potentially reveal insights to new physics beyond the Standard Model.

TECHNICAL CAPABILITIES: The Inflation Probe mission will be critical in order to make full-sky, uniformly well-calibrated and interconnected maps, to minimize systematic errors, and to avoid atmospheric effects. Multiple frequency bands (including some inaccessible from the ground) are required to maximize both sensitivity and foreground rejection, especially Galactic emission. The development of this mission stands in the context of plans for the next stage in ground-based observations for which the CMB community is optimizing mapping speed and sensitivity at frequencies accessible across available atmospheric windows to produce maps of the CMB. A satellite mission is unique in its ability to study large spatial scales with complete spectral coverage for removing polarized foregrounds. As has historically been the case, ground-based, sub-orbital, and orbital experiments are highly complementary [4]. Overlap in angular and frequency coverage will be essential for consistency in calibration and systematic control between these complementary approaches, as will a robust exchange of technological developments and analysis techniques, as well as joint analysis of final data products.

A design study will clearly be required to refine the Inflation Probe mission in light of new data from Planck and ground-based observations. Representative mission capabilities to address the proposed science include: $\sim 10^4$ dual polarization radiometric sensors with spectral coverage spanning approximately 30 to 300 GHz, a cold telescope with ~10 arc-minute or better angular resolution at 100-200 GHz, and a survey operational mode (*e.g.*, see [5]) in order to achieve a cosmic-variance limited measurement of the entire sky over a wide range of frequencies and angular scales in the presence of astrophysical foregrounds.

NEED FOR PROBE-CLASS MISSION: The consensus view of the U.S. community is that the appropriate choice for the Inflation Probe CMB polarization surveyor is a Probe-Class mission (between $250M - $1B) [6]. The specific implementation should be studied for presentation to the 2020 Decadal Review to refine and update the mission cost model. In conjunction with this effort it will be critical to take into account the scientific capabilities of other space-based CMB polarization opportunities (e.g., JAXA and NASA MO Litebird [7], NASA Midex [8], and ESA M-class missions [9]).

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1 *A White Paper by the Inflation Probe Science Interest Group (IPSIG) submitted in response to the "Cosmic Origins Program Analysis Group Call for White Papers: Probe-Class Astrophysics Mission Concepts" [1].*

NEW TECHNOLOGIES: Specific instrumentation challenges to implement the Inflation Probe mission are summarized in the "2015 PCOS Program Annual Technology Report (PATR)". The CMB Technology Roadmap ranked detector arrays as the highest priority, recommending a development strategy that utilizes detector systems in sub-orbital and ground-based polarization experiments. Significant progress has been made with a variety of detector approaches including antenna-coupling via planar transmission-line, micro-machined waveguide, and absorber-coupled filled array structures. We briefly summarize the key technologies identified for the Inflation Probe and their readiness [10]:

· **Advanced millimeter-wave focal plane arrays for CMB polarimetry (Current TRL ~4):** Arrays of detectors with background-limited sensitivity, dual-polarization detection capability, and control over systematic errors in multiple wavebands spanning centimeter to millimeter wavelengths are required to enable foreground removal for the Inflation Probe. The detectors must demonstrate high efficiency over a wide spectral range, be scalable to realize the required focal plane sensitivity, and be amenable to instrument architectures for space by allowing appropriate electromagnetic shielding, cosmic-ray immunity, and noise stability. Kilo-pixel scale detector arrays are operating in ground-based CMB polarization experiments. Balloon experiments presently operate such detector systems in a radiation environment analogous to that encountered in space.

· **Millimeter-wave optical elements (Current TRL ~2-5):** High-throughput telescope and optical elements with controlled polarization properties are required for the Inflation Probe. These optical systems require broadband millimeter-wave filters, coatings, and polarization control components as well as infrared thermal blocking filter technologies.

· **High-efficiency cooling systems for temperatures covering the range 20K to below 1K (Current TRL ~6):** Reliable and efficient continuous systems are needed for the Inflation Probe; these must have high thermal-lift capacity and be able to operate continuously. Cooling power must be increased beyond that provided by the Planck system to enable the use large of large focal planes. Approaches based on adiabatic demagnetization refrigeration (ADR), 3He sorption cooling, or closed-cycle dilution offer viable avenues to provide the desired capabilities.

REFERENCE – Selected Source Material

[1] Cosmic Origins (COR) Program Analysis Group Executive Committee, *"Cosmic Origins Program Analysis Group Call for White Papers: Probe-Class Astrophysics Mission Concepts"*, 2015, open letter to US Astronomical Community in preparation for National Academy of Sciences Mid-Decadal process; http://cor.gsfc.nasa.gov/copag/probe-study/Probe_Call.pdf

[2] National Research Council (NRC), "*New Worlds New Horizons in Astronomy and Astrophysics"*, 2010 Decadal Survey; http://www.nap.edu/openbook.php?record_id=12951

[3] NASA Strategic Roadmap, "*Enduring Quests, Daring Visions"*, 2013; http://science.nasa.gov/astrophysics/documents/

[4] DoE/NASA/NSF Inter-Agency Task Force on CMB Research, *"Task Force on Cosmic Microwave Background Research"*, R. Weiss (Chair), 2006; http://arxiv.org/abs/astro-ph/0604101

[5] J. Bock, *et al., "Study of the Experimental Probe of Inflationary Cosmology (EPIC)-Intermediate Mission for NASA's Einstein Inflation Probe"*, 2009; http://arxiv.org/abs/0906.1188

[6] Physics of the Cosmos Program Analysis Group (PhysPAG), *"Physics of the Cosmos Program Analysis Group (PhysPAG) Report on Flagship Mission Concepts to Study for the 2020 Decadal Survey"*, 2015, Response to Paul Hertz Flagship Mission Charge; http://pcos.gsfc.nasa.gov/docs/PCOS_facility_missions_report_final.pdf

[7] T. Matsumura, *et al., "Mission Design of LiteBIRD"*, 2014, Journal of Low Temperature Physics, Volume 176, Issue 5-6, pp. 733-740; http://arxiv.org/abs/1311.2847

[8] A. Kogut, *et al., "The Primordial Inflation Explorer (PIXIE)"*, 2014, Proceedings of the SPIE, Vol. 9143, id. 91431E17; http://arxiv.org/abs/1105.2044

[9] COrE Collaboration, *"COrE (Cosmic Origins Explorer) A White Paper"*, 2011; http://arxiv.org/abs/1102.2181

[10] NASA Physics of Cosmos (PCOS),*"PCOS Program Annual Technology Report (PATR)"*, 2015; http://pcos.gsfc.nasa.gov/docs/2015PCOSPATRRev1.pdf

Probe-class mission concepts for studying mHz gravitational waves

A white-paper submitted to the *Physics of the Cosmos Program Analysis Group: Probe-Class Astrophysics Mission Concepts.*

Massimo Tinto[1], Daniel B. DeBra[2], Sasha Buchman[2], Robert L. Byer[2]

[1] *Jet Propulsion Laboratory, California Institute of Technology, 4800 Grove Drive, Pasadena, CA 91109, U.S.A. – massimo.tinto@jpl.nasa.gov*

[2] *Hansen Experimental Physics Laboratory, Stanford University, Stanford, California, 94305, U.S.A.*

1. SCIENCE DRIVERS

The direct observation of a gravitational wave (GW) signal from the coalescence of two in-spiraling black-holes, announced by LIGO on Thursday, February 11, 2016, represents one of the greatest triumphs in experimental physics today and the beginning of a new era for astronomy. Ground-based detectors such as LIGO are sensitive to the kHz GW band with the seismic noise-wall preventing them from being sensitive below ~ 10 Hz. In order to make astronomical observations in the mHz band, where GW signals are expected to be stronger and larger in number, we propose a radically new concept for a space-based GW interferometer within the probe-class missions. With such a detector we will be able to observe massive (10^4 – 10^6 M_0) and supermassive (10^7 – 10^9 M_0) in spiraling binaries black-holes, identify their formation mechanism and their roles in the evolution of galaxies, probe the space-time geometry imprinted into the GW waveforms generated by small objects spiraling into massive black-holes, and identify the spatial and mass-distribution of the hundreds of millions of white-dwarfs binaries in our own galaxy. These were the primary LISA scientific objectives, and we believe a probe-class mission similar to the ones described below will be able to deliver most (if not all of) them at a significantly reduced cost.

2. TECHINCAL CAPABILITIES

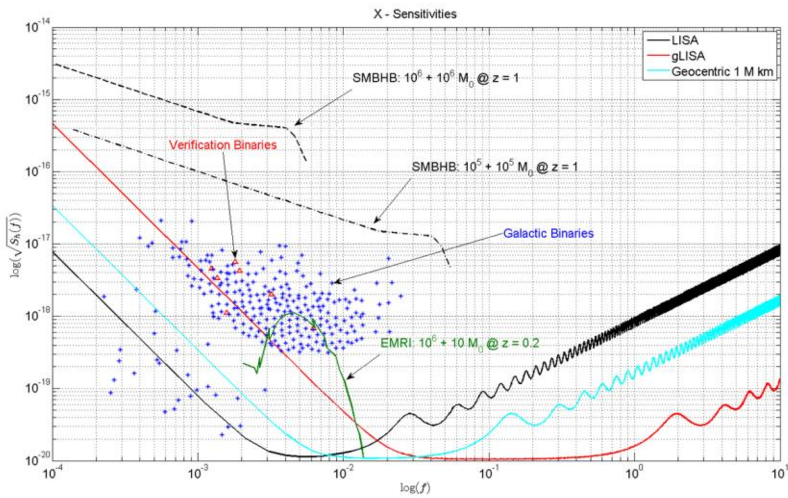
After the end of the NASA-ESA partnership in 2011 and the conclusions reached by the NASA GW RFI study exercise, it became quite clear that, to fly a space-based GW interferometer at a cost lower than $1B, a thinking paradigm shift was needed. It was within this spirit that in 2013 we begun to explore the options offered by the aerospace industry. Recent technological developments to meet the growing demands for low-cost satellites and launching vehicles, together with the existing NASA program for flying scientific instruments onboard geostationary commercial satellites (COMSATS) [1] have opened up a broader set of opportunities of short development cycle and cost reductions for GW missions. With knowledge of this new development, we explored the scientific, technical, programmatic, and cost advantages of flying a geocentric gravitational wave mission with "off-the-shelf" satellites or by hosting the necessary instrumentation onboard three geostationary comsats.

The proposed "dedicated" geocentric mission concept has previously been studied at Stanford, and more details can be found in [2], while the "comsat option" has been discussed at some length in [3, 4, 5]. Both mission concepts have recently gone through a JPL A-TEAM study exercise and their costs have been estimated to be $900M (dedicated geocentric) and $560M (geostationary COMSATS) respectively for a 2 year mission duration. Their expected scientific capabilities are summarized by the sensitivity plot below, which also includes for comparison the nominal LISA sensitivity together with the strengths of various gravitational wave sources expected to radiate in this frequency band.

3. NEW TECHNOLOGIES

Under the assumption of a successful outcome of the LISA Pathfinder mission, the technology needed by our proposed mission concepts will be at a sufficiently high level of maturity for being more quickly developed here in the US. The experimental efforts at Stanford on the Modular Gravitational Reference Sensor (MGRS) design [6] have started to come to fruition, giving us confidence to achieve the required acceleration noise level ($< 3 \times 10^{-15}$ m/s^2 Hz$^{-1/2}$) adopted in the derivation of the sensitivity curves shown in the figure below by the year 2020.

For the geostationary comsat mission option we derived a drag-free design (the so called "two-stage drag-free system") that reaches the required level of inertia onboard these large and massive satellites. The most interesting feature of this design is that it does not require the use of μN thrusters. Briefly, the two-stage drag-free system can be envisioned by thinking of a small satellite (the "hosted satellite"), residing inside an enclosure located on the nadir-pointing (Earth-pointing) deck of the comsat. It carries onboard the MGRS with its free-floating, spinning, spherical proof-mass (PM). Sensors continuously monitor the position and velocity of the hosted satellite relative to the comsat while now, rather than relying on μN thrusters, electro-magnetic actuators attached to the inside walls of the nadir enclosure act on the hosted satellite to keep it centered on its PM. These actuators, which already exist as they form the key-technology element developed at Stanford for the LIGO active seismic isolation system, can operate within a gap-distance of 1-2 mm. Since the comsat may experience a non-gravitational acceleration of about 10^{-7} m/s^2 due to solar radiation pressure and disturbances caused by its mechanisms, in order to avoid interruption of data acquisition every 140 s or so as the onboard satellite would move by 1 mm over this time scale, additional thrusters (such as cold-gas or ion thrusters) driven by the onboard sensors can act on the comsat to compensate for the non-gravitational acceleration due to solar radiation pressure. This operational configuration allows the hosted satellite to continuously operate in its drag-free configuration and perform heterodyne measurements by exchanging laser beams with the hosted satellites onboard the other two comsats. Although this can be done most effectively by using spherical proof masses, it could also be implemented with a cubic proof-mass.



Sensitivities achievable with the geostationary comsats (labelled **gLISA,** red line) mission, the Geocentric mission (cyan line) and by LISA. The shorter (~73,000 km) armlength of the geostationary configuration results into a sensitivity-degradation by a factor of ~ 70 over that of LISA in the lower-part of the accessible frequency band (10^{-4} – $2x10^{-2}$) Hz, and an improvement by the same factor in the remaining part of the band ($2x10^{-2}$ – 10) Hz. Both our proposed missions will meet the PCOS science goals within the cost budget of a probe-class mission.

4. REASONS WHY A PROBE-CLASS MISSION IS NEEDED

Due to the nature of the experiment, three satellites (whether dedicated or comsats) will need to be flown to perform the heterodyne measurements required to generate the interferometric data. The resulting mission costs therefore exceed the cost caps associated with the Explorer and Mid-Ex programs, and are below the cost cap of a probe-class mission.

5. COST ESTIMATE

Earlier this month (February 2016), an A-TEAM mission study was performed at JPL. Its objectives were to study our two mission concepts and identify their costs and scientific capabilities. The resulted costs ($560M and $900M) for a nominal 2 year mission operation give us confidence that both mission concepts could become a reality within the cost cap associated with a probe-class mission.

REFERENCES

[1] Common Instrument Interface Project, Hosted Payload Guidelines Document, NASA Document No: CII-CI 0001 Version: Rev A (Effective Date: 04/11/2013).

[2] J.W. Conklin, *et al.*, "LAGRANGE: LAser GRavitational-wave ANtenna at GEo-lunar Lagrange points", http://arxiv.org/abs/1111.5264

[3] M. Tinto, D. DeBra, S. Buchman, and S. Tilley, "gLISA: geosynchronous laser interferometer space antenna concepts with off-the-shelf satellites", *Review of Scientific Instruments*, **86**, 014501 (2015).

[4] M. Tinto, J.C.N. de Araujio, O.Aguiar, and M.E. Alves and M. Tinto, "Searching for Gravitational Waves with a Geostationary Interferometer", *Astroparticle Physics*, **48**, 50-60 (2013).

[5] M. Tinto, J.C.N. de Araujo, H.K. Kuga, M.E.S. Alves, and O.D. Aguiar, *Class. Quantum Grav.* **32**, 185017 (2015)

[6] Ke-Xun Sun, G. Allen, S. Buchman, D. DeBra, R. Byer, *Classical Quantum Gravity*, **22**, S287 (2005).

Science Drivers: We propose a geocentric laser interferometer for the observation of both massive and stellar-mass black-hole binaries. Such an interferometer, which would possess armlengths $\mathcal{O}(10)$–$\mathcal{O}(100)$ shorter than the nominal design for the evolving Laser Interferometer Space Antenna (eLISA) (constrained on the low end by Earth's atmosphere and on the high end by orbital stability and phasemeter requirements), would have a sensitive band that is optimal for observing the most common black-hole mergers in the Universe - between black-hole binaries formed from the mergers of spiral and dwarf galaxies, and between intermediate-mass black-hole binaries formed in globular clusters. In addition, an observatory of this scale would also have an optimal sensitive band for detecting the last few years preceding merger of stellar-mass binaries containing black holes and/or neutron stars (see Figure 1). Observing such systems in advance of their mergers would make it possible to precisely localize the eventual mergers in both space and time, thereby making it possible to observe electromagnetic counterparts to these gravitational-wave signals. Even without observing the mergers, which occur at higher frequencies better explored by ground-based detectors, such counterpart observations would allow us to constrain dark energy by providing several hundred paired redshift-luminosity distance measurements. In addition, it is likely that ground-based observatories would still be in operation during the lifetime of the proposed mission, given the success of Advanced LIGO and the existing plans for third, fourth, and fifth generation detectors over the next two decades. Therefore, by combining the observation of the mergers of compact binaries with the simultaneous observation of electromagnetic emission (which would be made possible by the advanced warning from the space-based detector), we could precisely probe dark energy, measure the neutron star equation of state in fine detail (thereby informing our understanding of particle physics far above nuclear densities), and explore the gaseous and/or electromagnetic environments of merging black holes, to name only a few of the revolutionary possibilities of such a mission.

As was demonstrated during the 2011–2012 Gravitational Wave Mission Concept Study, the most compelling scientific rationale for short geocentric orbits was that it would result in dramatically improved measurement capabilities, despite having a lower signal-to-noise ratio for more massive systems. The typical level of improvement for a realistic astrophysical population would be **2–3 orders of magnitude in every parameter** relative to eLISA, due primarily to the higher frequency of the orbit-induced amplitude modulations for observed signals, which directly improves source localization dramatically, and also allows sidebands to occur at more optimal frequencies for measuring other source parameters. This tremendous improvement in the level of precision measurement would greatly aid in our understanding of astrophysical populations, and would also allow us to localize sources to a **single host galaxy**, rather than an error voxel containing many thousands of galaxies, which would help substantially with identifying electromagnetic counterparts.

Technical Considerations: The proposed interferometer would consist of either three or four satellites in geocentric orbit, depending on the specific design choices adopted, particularly the orbital configuration. The observatory would possess 2 – 4 equal arms measuring 20000 – 100000 km on a side, with the smallest option (hereafter option A) requiring either an increase in the number of arms and satellites or else a decrease in the number of functional arms relative to eLISA due to orbital requirements (essentially, the Earth itself would be in the lasers' path otherwise). The advantage of this design choice would be the availability of sun-synchronous orbits, which would yield greater thermal stability (constant face to the Sun, potential to minimize variations of Earth-shine) and would avoid exposing the telescope to direct sunlight. However, if a solar filter or a retractable shutter for the telescope can be developed and implemented, and if detailed thermal modeling can demonstrate that the performance impact of the resulting thermal variations can be mitigated, then a “traditional” equilateral constellation near or beyond geostationary orbit could be employed (hereafter option B). Communications are simplified in either case, and the possibility of a servicing mission in the event of a single satellite failure is viable. The satellites are identical, and the thrust requirements for a 120 degree phase change for 2 satellites are minimal. The thrusters can supply the necessary thrust, so no propulsion module would be needed for the proposed design.

A perceived disadvantage for option A is the potential for gravity gradient noise to become nonnegligible for the orbits we are considering. However, we note that the relative frequency between the satellite position and the Earth's rotation is well below the sensitive band; since gravity gradient noise falls off rapidly above this frequency, it would only be a concern for lower Earth orbits than we are considering.

A perceived disadvantage for option B is the presumed need for station-keeping, since the Sun and Moon provide torques out of the constellation's orbital plane, which would cause a relative drift among the sciencecrafts. However, this drift is at the level of $\Delta v \sim 45$ m/s each year, and is primarily directed out of the plane of measurement, which implies a Doppler shift well below 45 MHz per year for a micrometer wavelength laser. Conservatively estimating the Doppler shift at 25 MHz, phasemeter sampling at 50 MHz would therefore allow operation for at least two years without station keeping. Such a sampling rate is within the capabilities of available phasemeters planned for the nominal eLISA design. The mission lifetime would therefore be limited by the phasemeter capabilities in that scenario, although it is more likely that cost would determine the mission lifetime, with the lifetime determining the phasemeter requirements.

New Technologies: The technology required for the proposed design will be similar to the developmental requirements for eLISA. The nominal design requirement for the acceleration noise achieved by the Disturbance Reduction System (DRS) will already be demonstrated by LISA Pathfinder. The optical path components will be a larger scale version (larger telescope, higher laser power, etc.) of the technologies that will be demonstrated by the Grace Follow-On mission. One technology with more stringent requirements than eLISA would be the phasemeter, although the nominal phasemeter planned for eLISA could facilitate a mission lifetime of at least 2 years without station keeping. A detailed thermal study would be required

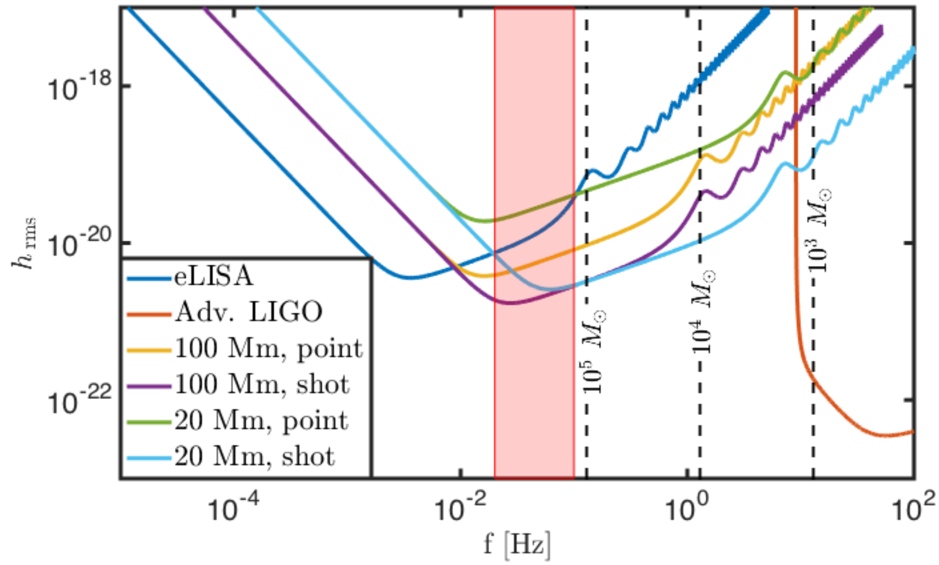


Figure 1: The strain sensitivities of eLISA, Advanced LIGO, and several design options for the proposed mission. The smaller armed design would execute sun-synchronous orbits with greater thermal and orbital stability, but would require either one less arm or an additional satellite relative to eLISA in order to perform its measurement. The longer armed design would require a sun filter or a shutter and would possess poorer thermal stability, but it could operate with the traditional equilateral LISA-like configuration. For each scenario, we show a case where pointing noise is suppressed below shot noise, and another where it can only be suppressed to the pm/$\sqrt{\rm Hz}$ level. We also mark the typical merger frequencies for binaries with total system masses of 10^3, 10^4, and $10^5\ M_\odot$, to show that this loudest, most dynamical, most information-rich part of the signal would be more sensitively measured by the proposed concepts than by eLISA. We emphasize that these three masses represent the range of expected masses for the sources that a space-based detector might actually observe. We also show a shaded region, which indicates the frequency range at which stellar-mass binaries, from 10–100 $M_\odot$, whose mergers could be seen by a ground-based detector, would emit at the start of their final year prior to merger.

to determine whether option B possesses sufficient thermal stability. Option B will likely require a solar shield to mitigate thermal variability, whereas option A *c*ould require some shielding from Earth-shine (although preliminary estimates suggest this might not be necessary). If option B proves thermally viable, then development of an adequate solar filter would be necessary. The necessary filtering capabilities have been demonstrated for the Omega mission concept, but additional development would be required to space qualify an adequate filter.

Probe-Class Justification: While we emphasize that the design options described here are motivated by optimally targeting the described sources, which occur at frequencies significantly above the most sensitive frequencies of eLISA, we nonetheless conclude that every monetarily significant design variation relative to eLISA serves to decrease the overall mission cost. By virtue of its smaller armlength and orbital characteristics, the proposed observatory will have significantly reduced requirements for the telescope mirror size, laser power, and propulsion (no propulsion module would be needed). Due to the substantial reduction in overall mass and orbital Δv, we expect a significant reduction in launch cost; preliminary estimates suggest that the lower cost Falcon 9 (Block 2) launch vehicle would be sufficient, but we note that the geocentric orbits admit the possibility of shared launches and/or having multiple smaller launches to further reduce cost. Though motivated by the science drivers, the design changes nonetheless serve to decrease the overall budget from L-class to probe-class.

Cost: The lighter mass and smaller Δv orbit will be the principle areas of savings relative to the nominal eLISA design. We can follow the costing approach of subtracting cost from the $1.8B SGO high price point in the 2011–2012 Mission Concept Study (based on LISA with a less expensive launch vehicle). The Falcon 9 (Block 2) from SpaceX would be the most cost effective single launch vehicle capable of supporting the launch mass, for a cost savings of $300M relative to SGO high, with additional savings of ∼$100M possible if we can arrange multiple shared launches. A reduced 2 year mission lifetime would provide a further savings of $200M in personnel cost, although this additional savings directly impacts the achievement of the science goals. The proposed design would not require a propulsion module, since the thrusters planned for SGO or eLISA would be capable of executing the necessary maneuvers; this would provide an additional savings of $100M. The final cost estimate, performed in this fashion, is therefore $1.1B – $1.2B. However, we emphasize that if we instead adopt the Grace Follow-On mission as our baseline, then starting from $450M, and adding costs from the Mission Concept Study for the DRS ($50M), increased mass/power and their impact on launch requirements ($100M), upgraded laser and optics ($150M), and phasemeter ($80M), we find a total cost of $830M. Therefore, it is our expectation that a large portion of the design-option parameter space will fit within the probe-class cost window.

"99 Luftballons"

Tim Eifler (JPL/CalTech) email: tim.eifler@jpl.nasa.gov

Discover how the universe works, explore how it began and evolved is one of NASA's major mission objectives (NASA Strategic Plan 2014). The nature of cosmic acceleration, the mass of neutrinos, testing the laws of gravity on very large scales, constraining inflationary scenarios, and understanding the formation and evolution of galaxies and cosmic structures are at the core of several NASA missions. The James Webb Space Telescope (JWST), Euclid, and the Wide-Field Infrared Survey Telescope (WFIRST), but also DOE's ground-based Large Synoptic Survey Telescope (LSST) focus on these areas of astrophysical research.

These missions are highly synergistic: LSST will cover 18,000 deg^2 in 6 optical bands to ~27th i-band magnitude depth; it's image quality however is limited by Earth's atmosphere. Euclid will cover 15,000 deg^2 with exquisite image quality but it is 2.5 magnitudes shallower, it only uses one broad optical band, and it only overlaps with LSST for ~6,000 deg^2. WFIRST will be as deep as LSST but will only cover 2,100 deg^2. When combined and carefully coordinated these missions are superior to the sum of their parts, however they fall short of the "99 Luftballon" mission concept.

This concept is based on NASA's recently developed Ultra-Long Duration Balloon (ULDB) capability, which enables a combination of diffraction limited angular resolution, extreme stability, space-like backgrounds, and long mission duration (~100 days). The combination of lightweight mirrors and advanced detector technology enables the design of large ULDB missions (2+m mirror with Gpix camera) that have significant advantages in wavelength coverage and image quality compared to the ground and significant cost advantages compared to space missions.

It is only logical to consider the science potential of multiple large ULDB missions that follow a similar design; we envision a wide-field camera similar to Euclid VIS instrument, which observes in 1 broad optical band (550-900nm) to maximize photon throughput. Table 1 shows our assumed mission parameters for a single Small (1.2m mirror diameter), Medium (1.8m), Large (2.4m) ULDB flight. We note that in addition to the mirror size (Table 1 actually specifies the mirror area), we increase the camera Field-of-View (FoV) when going from Small to Large, which implies a significant increase of number of pixels of the detector. The last row in Table 1 shows the covered area of the ULDB mission compared to the 6-year Euclid mission.

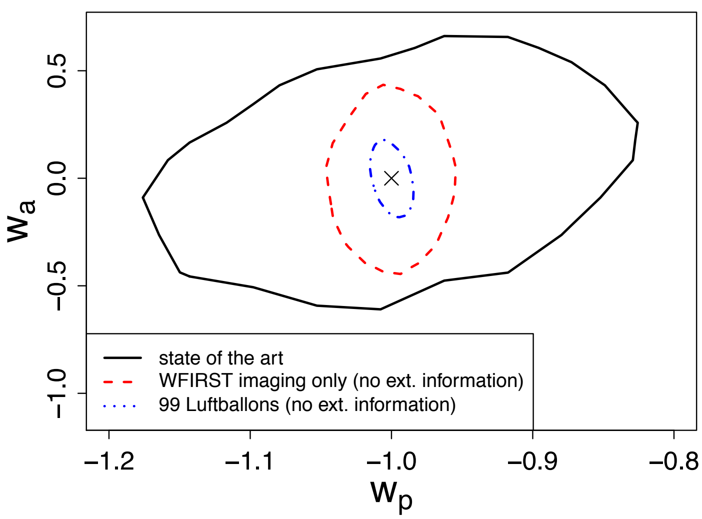
Table 1. Assumed mission parameters for a Small, Medium, Large ULDB. The last row contains the computed survey area at Euclid depth.

	Euclid	Small	Medium	Large
Dark time per day (h)	24	12	12	12
Mission duration (d)	2195	100	100	100
Camera FoV (deg^2)	0.57	1	1.5	2
Primary Mirror (m^2)	1.13	1.13	2.55	4.52
Survey Strategy	0.6	1	1	1
$A_{\rm survey}$ (deg^2, Euclid depth)	15,000	1,000	3,382	7,993

Following Table 1 we find that 2 Large ULDB missions can cover as much as 16,000 deg^2 at Euclid depth and imaging quality. An increase of the survey depth from 24.5 to 27 (aka LSST or WFIRST depth) increases the required survey time by a factor of ~10 (flux scales as $2.5^{(27-24.5)}$), which translates to approximately 20 Large ULDB missions for the 16,000 deg^2.

An improved version of this mission concept would replace the broad 550-900nm optical band with narrower multi-band photometry. This allows for obtaining redshift information of the observed galaxies and it enables more precise modeling of the (wavelength dependent) PSF. A first order calculation (assuming that signal-to-noise scales with the width of the filter) shows that 99 ULDBs can cover the 16,000 deg^2 at LSST/WFIRST depth in 4 (partly overlapping) bands, each of width ~280 nm, covering 270-1000nm wavelength. This exceeds LSST's wavelength coverage and it indicates the superior imaging speed and wavelength coverage in the Blue-UV from a sub-orbital platform compared to ground-based observations. The exact parameters of the 99 Luftballons probe mission (depth, area, number of photometric bands) should be subject to further study; minor reductions in survey depth can be used to increase the number of photometric bands. **In combination these 99 ULDB missions approach the science return of an LSST telescope in space, hence they reach a completely new level of discovery potential compared to currently planned post-2020 astrophysics missions.**

As an example, we forecast the constraining power of the 99 Luftballons mission on the cosmic acceleration parameters w_p-w_a (see Fig. 1). We emphasize however that myriad science areas beyond cosmic acceleration (galaxy formation, transients, nearby galaxies, exoplanets, Milky Way studies, etc.) will benefit from this type of imaging survey.



Cosmic Acceleration Forecasts of the WFIRST imaging survey and the 99 Luftballons mission that include several cosmological probes: Cosmic Shear, Galaxy Galaxy Lensing, and Galaxy Clustering. The state of the art constraints combine information from Planck, BOSS (Baryon Oscillation Spectroscopic Survey), and JLA (Joint Lightcurve Analysis) supernova. Forecasts are based on the CosmoLike forecasting software (Krause&Eifler 2016).

The implementation of the 99 Luftballons concept is challenging, e.g. the infrastructure to launch this many ULDBs over only a couple of years does not yet exist. In addition, we note that flying such a wide-field detector array and large telescope mirror on a balloon has not happened to date (the BLAST mission has already flown a 2m primary mirror though).

On the other hand the modularity of this concept has enormous advantages:

- Updated instrumentation is easy to implement
- Improvements to the mission strategy are easy to implement
- Risk minimization: a single mission failure is of hardly any consequence to the probe
- Cost savings through mass production of the ULDBs and instruments
- Probability to recover and reuse the instrument is larger than 0%.
- Enormous synergistic potential with space-based IR missions (JWST, WFIRST)

The idea to design a probe mission as a multitude of ULDBs (at ~10M USD per ULDB) is certainly unorthodox, however the science return on astrophysics rivals that of a 6m class telescope in space. In combination with IR information from space missions **one can think of the 99 Luftballon mission as NASA's HST COSMOS survey, but covering 16,000 deg^2 instead of 1.6 deg^2.**

References: Krause, E., Eifler,T., CosmoLike - Cosmological Likelihood Analyses for Photometric Galaxy Surveys, *eprint arXiv:1601.05779* (2016)