2016 NASA Astrophysics Senior Review

22-25 February, 2016

PANEL

Chair: Megan Donahue (Michigan State University)

Mark Bautz (Massachusetts Institute of Technology)

Richard Green (University of Arizona)

Günther Hasinger (University of Hawaii at Manoa)

Lisa Kaltenegger (Cornell University)

Henric Krawczynski (Washington University in St. Louis)

Andrew MacFadyen (New York University)

Dan McCammon (University of Wisconsin)

Rebecca Oppenheimer (American Museum of Natural History)

Paula Szkody (University of Washington)

Dennis Zaritsky (University of Arizona)

FINAL REPORT DELIVERED TO

Daniel Evans, Program Scientist, Astrophysics Division, NASA Headquarters

Jeffrey Hayes, Program Executive, Astrophysics Division, NASA Headquarters

Paul Hertz, Director, Astrophysics Division, NASA Headquarters

MAIN REPORT

INTRODUCTION

Every two years NASA's Astrophysics Division is required by the NASA Authorization Act of 2005 to conduct a "Senior Review" in order to evaluate operating missions in Phase E of their lifecycles that are seeking to continue operations for augmentation of science returns on the initial investment. This review is the highest level peer-review process in the Astrophysics Division. Many spacecraft can continue to operate beyond the originally proposed mission duration and remain extremely valuable assets with high scientific return. In some cases, the extended missions address similar science goals as the original missions but in greater depth; in other cases, the extended missions open completely new science investigations which cannot be achieved with the current fleet of NASA observatories nor with upcoming new missions. The Senior Review Panel (hereafter SR2016 panel) is tasked with evaluating and ranking the missions, and recommending distribution of available funds from the Missions Operations and Data Analysis (MO&DA) budget line, primarily based on the expected value of the science returns for each mission. The SR2016 panel reviewed six continuing missions. In 2016, the flagship missions of Hubble Space Telescope and the Chandra X-ray Observatory were reviewed by separate, individual committees.

Charge to the 2016 Senior Review Panel

This comparative review assesses the merits and performance of the following six missions (in alphabetical order): Fermi, K2, NuSTAR, Spitzer, Swift, and XMM-Newton, according to the following charges requested of the SR2016 panel by NASA:

1. Use the ranking criteria (defined in Ranking Methodology) to individually assess each project over the funding period FY17 and FY18 and the extended funding period FY19 and FY20. This charge includes providing an adjectival assessment for each of the three categories of ranking criteria as well as an overall assessment. (A description of those adjectives is provided in Table 1.)
2. Use the ranking criteria to rank the projects over the funding period FY17 and FY18 and the extended funding period FY19 and FY20. This rank includes programmatic concerns of synergies and portfolio balance.
3. Provide findings to assist with an implementation strategy for the Astrophysics Division portfolio of operating missions for FY17 through FY20, including an appropriate mix of:
    a. Continuation of projects at their "in-guide" level as currently baselined.
    b. Continuation of projects with either enhancements or reductions to their in-guide budgets, the boundaries of which are defined by the "over-guide" and "under-guide" levels proposed by each mission or other considerations of the SR2016 panel.
    c. Mission extensions beyond the prime mission phase, subject to the "Mission Extension Paradigm". There were no missions under consideration in this category for 2016.
    d. Termination of projects.

According to this charge, the findings must take into account the following factors:

1. The panel's assessments and relative rankings of the missions under consideration.
2. The overall strength and ability of the resulting mission portfolio, including both the missions under consideration, as well as new missions expected to be launched, to fulfill the Astrophysics Division priorities from FY17 through FY20, as represented in the 2014 SMD Science Plan and in the context of the 2010 Astrophysics Decadal Survey.
3. The projected science returns of the missions under review with the potential advances to be gained from an alternative strategy of increased funding for other Division priorities.
4. The scientific tradeoffs and opportunity costs involved in extending existing projects versus reducing or terminating them and using that funding for future flight opportunities, most especially in light of new Astrophysics missions expected to be launched.

RANKING METHODOLOGY

In the interests of fulfilling the part of the SR2016 panel charge to rank the missions first on science, second on relevance and responsiveness, and third on technical capability and cost reasonableness, the SR2016 panel was charged with the following procedure to evaluate each mission based on the following NASA-defined criteria and weighting factors:

A. Science Program (40% weight)

1. Uniqueness and overall strength of the science case
2. Scientific Output and return of investment over the proposed funding period
3. Synergy with the Astrophysics Division Mission Portfolio
4. Quality of archiving, distribution and usability

B. Relevance and Responsiveness (30% weight)

1. Relevance to the research objectives in the SMD and 2010 Astrophysics Decadal Survey
2. Progress toward achieving any Primary Mission Objectives (PMOs) identified by the 2014 Senior Review (SR)
3. Performance of addressing any finding of the 2014 SR

C. Technical Capability and Cost Reasonableness (30% weight)

1. Cost efficiency in terms of meeting proposed goals
2. Health of the spacecraft and operating model
3. Operating Costs

The individual missions were discussed in terms of these three criteria. The discussion and overall assessment of each mission are described in the individual mission sections at the end of this report.

Table 1: Descriptions of Adjectival Ratings in Table 2.

Adjectival description	**Basis**
Excellent	A thorough, and compelling proposal of exceptional merit that fully responds to the objectives of the CfP as documented by numerous or significant strengths and with no major weaknesses.
Very Good	A competent proposal of high merit that fully responds to the objectives of the CfP, whose strengths fully outbalance any weaknesses and none of those weaknesses constitute fatal flaws.
Good	A competent proposal that represents a credible response to the CfP, whose strengths and weaknesses essentially balance each other.
Fair	A proposal that provides a nominal response to the CfP but whose weaknesses outweigh any strengths.
Poor	A seriously flawed proposal having one or more major weaknesses that constitute fatal flaws.

RANKING RESULTS

A summary of our findings for each mission is included in the individual Mission Assessments in the latter half of this report. Each mission submitted a proposal which was read and evaluated by the panelists prior to the in-person meeting. Mission representatives presented a 60 minute overview of their proposal and updated the panel on any science or mission news, followed by 30 minutes of discussion with the panel. Each mission was discussed by the SR2016 panel in closed session on the day following its mission team presentation. After this process was complete, the panelists submitted numerical scores corresponding to the adjectival rankings in Table 1. These scores were compiled by the two program managers who completed a median of the panelists' ratings for each of the criteria A, B, and C for each mission. The composite scores were combined to create an overall score for each mission using the weighting factors given above. The mean scores, translated to the adjectival scores, are reported in Table 2. The adjectival scores capture the information contained in the numerical scores with sufficient precision to reflect the evaluation of the panel. The rankings, particularly the relative ranks of the three pairs of missions: (K2/Swift), (XMM/NuSTAR), and (Fermi/Spitzer) as the top, middle and the bottom-ranked pairs, was not affected by choice to show the mean over the median calculation.

The voting methods used allowed for anonymity and independence among the panelists in their ratings. It is extremely important to note that the overall rankings for all of the proposals were Excellent/Very Good to Excellent. The science case and relevance for all missions were also rated as either Excellent or Excellent/Very Good. The ranking in Table 3 was compiled from ordinal rankings of the six missions in terms of science and programmatics. Each panelist, in addition to scoring each mission, ranked the missions from 1 to 6. Those rankings were combined and close ties were resolved by pairwise voting.

The SR2016 panel recommends funding all of the missions based on the science cases presented. In addition, the panel judged that the reviewed missions had unique capabilities and exploited aspects of the spacecraft that allowed for truly new types of science. The portfolio of missions is scientifically stronger as an ensemble: the value of the portfolio as a whole is higher than the simple sum of its parts.

Table 2. Mean of panel rating matrix for the individual missions. Each row corresponds to a mission and each column corresponds to a criterion category.

Criteria	**Science (A)**	**Relevance (B)**	**Cost (C)**	**Total**
K2	E	E	E	E
Swift	E/VG	E	E	E
XMM	E/VG	E/VG	E	E/VG
NuSTAR	E/VG	E/VG	E	E/VG
Spitzer	E/VG	E/VG	VG	E/VG
Fermi	E/VG	E/VG	VG	E/VG

Scores: E=Excellent, E/VG = Excellent/Very Good, VG=Very Good

Table 3: Programmatic and scientific ranking of all missions ranked 1-6.

Mission	**Ranking**
Swift	1
K2	2
NuSTAR	3
XMM	4
Fermi	5
Spitzer	6

Finding for Overguide Request Ranking. The SR2016 panel also considered and ranked the over-guide requests above the nominal continuation budgets. The Swift augmentation of its automation, which would enable the scheduling of 400-500 targets per day of $200K was ranked above the second highest priority, the XMM request for a $1M augmentation of the funding of its GO program. The Swift request for

$200K to augment its GI program was ranked third, and the remaining Swift requests were considered good to do if other economies were found within the Swift program.

OVERALL FINDING

The SR2016 panel finds no scientific reason to discontinue or significantly reduce the funding or scope any of the six missions under this review.

The SR2016 panel found no major issues relating to science, relevance, or technical risk for any of these missions. All of these missions lie well above our threshold of merit. The proposals were of exceptional quality and completeness, fully responsive to the call, with at most minor weaknesses or concerns identified. **We strongly encourage NASA to find a way to continue all of these missions at their full funding level.**

As discussed in Ranking Results, the SR2016 panel provides a rank-ordered priority for the six missions that includes programmatic considerations, such as balance. Each mission was evaluated on three review criteria and a weighted total, which are reported here with adjectival ratings. The adjectival ratings adequately capture the similarities in the scores and the panel's absolute assessment of the excellence of the programs. (Every program achieved a rating of Excellent or Excellent/Very Good in nearly all criteria.) In addition, within each mission, we have prioritized requests and activities based on their scientific and programmatic value to the overall portfolio, and to astrophysics overall.

In light of budgetary uncertainties, the panel decided to consider two scenarios: (1) the missions can all be funded at their requested levels (including overguides) and (2) the funding for the SR mission wedge is insufficient for (1), in which case there is a shortfall. The Senior Review panel provided guidance to NASA for prioritizing reductions to the missions depending on how large a shortfall might manifest itself once the actual budget is known.

The full funding scenario is the one strongly advocated by the SR panel. All the missions are highly meritorious by the absolute evaluations provided. They constitute a balanced and highly productive portfolio, and a cost-effective leverage of substantial capital investment in flight hardware. The missions have taken creative directions to accommodate new, forefront scientific investigations.

DISCUSSION

General background. The universe does not recognize wavelength boundaries. Light from the universe carries precious information, streaming to us at wavelengths we classify as radio, infrared, visible, UV, X-ray, gamma-ray. However to decode this information we usually need access to more than one spectral domain. For sources that explode or otherwise vary, we need simultaneous or nearly simultaneous spectral coverage from observatories specializing in different parts of the spectrum. Some types of light are completely inaccessible from the ground (UV, X-ray, some IR and gamma-ray); even visible and infrared observations from space transform small (~2 meter) telescopes to Great Observatories because they are above the atmosphere, a source of distortion and background for ground-based observatories. The

Hubble Space Telescope brilliantly shows us the awesome power of high angular resolution images, but we also need, for example, high resolution spectroscopy to reveal the velocities, composition, temperatures, gas densities and other properties of distant astronomical objects. Since no single observatory can do all of these things, we require a portfolio of NASA missions working together to address our major scientific questions. The SR2016 panel was tasked with assessing these missions both individually and in terms of their contribution to the overall program.

The SR2016 panel finds that each of these missions is producing and will continue to produce substantial and excellent science. Furthermore, the demonstrated synergy between these operating missions, HST, Chandra, and other significant astronomical assets (gravitational wave detectors, ALMA, ground-based radio to gamma-ray observatories, cosmic ray observatories, and neutrino observatories) shows that maintaining these capabilities has been a wise investment. Every mission in the portfolio has science-critical synergies with other operating missions. For example, NuSTAR, XMM and Swift have combined soft and hard X-ray spectroscopic observations to resolve questions about the physics of black hole binaries and accretion onto supermassive black holes. Fermi and Swift make a formidable team in monitoring the gamma ray transient sky. K2, whose future performance level was not certain in 2014, is now producing photometry nearly at the level of precision of the original Kepler mission in campaigns that are being supported by Swift coverage in the X-ray and UV. K2 and Spitzer have partnered to characterize the new Earth-sized planets being discovered by K2 with follow-up observations by Spitzer. The highest redshift galaxies, likely to be among the first targets of the James Webb Space Telescope, were discovered by the potent coupling of the Hubble Space Telescope with the longer wavelength coverage of the Spitzer Space Telescope. More of these scientific cases are discussed in the individual mission sections of this report. **The scientific value of the complete Astrophysics Senior Review 2016 portfolio is greater than the sum of its parts.**

The SR2016 panel evaluated the scientific value of the activities proposed for each mission, within the context of that mission, and in the broader context of on-going astrophysics research and future opportunities.

Discussion of Guest Observer/Guest Investigator (GO/GI) Funding

The SR2016 panel was tasked with giving NASA guidance on the scientific priority of activities by these missions. Overall, we would like to call out the importance of the GO/GI programs in each of these missions. Many of the science highlights of the past originated not from the mission science teams, but from the innovative and original ideas that emerged from competitive community proposal calls. The larger community consistently generates excellent science, which drives the observatories to evolve rapidly in response to scientific opportunity, to respond quickly to discoveries, and to achieve greater scientific understanding of the universe than they would have had they maintained the same scientific program that was planned prior to launch or even during the prime mission.

To preserve more operations support, the panel discussed but disfavored reductions of GO/GI funding. The proposed total for all missions of FY17 GO funding is \$16.2M. The powerful argument for preserving GO funding is maintaining scientific productivity, the purpose of mission support. It is also the case that cuts in GO funding affect junior scientists far more adversely. Furthermore, the GO/GI programs provide the resources and diversity that spur innovative and creative uses of the observatories to explore questions and exploit capabilities that were never anticipated prior to launch or even prior to the end of the prime mission. Any across-the-board reduction to GO/GI funding would cause severe damage to the scientific productivity of the missions, while the astronomical field as a whole would incur severe losses in terms of future capacity because of the disproportionate penalty paid by the youngest members of the community.

In financially difficult times, trades must be made between maintaining a healthy GO program and operating the mission at full capabilities. If savings must be made, the opportunity costs of cutting science funding must be traded against the loss of some operational capabilities or the increase of mission risks. The SR2016 panel does not have the information or the expertise needed to assess in any detailed way how a mission could be reduced in detail. The general sense of the panel was that if any mission's budget had to be cut, the first action would be a holistic trade study of GO or GI funding and operational cuts, down to a nominal level identified by each operating mission as the minimum needed to keep the observatory running. If possible, reductions to data analysis funding should be made as temporary cuts or in the form of deferments to future year support.

Discussion of Fermi and Spitzer

Fermi and Spitzer are the missions with the largest projected costs. These missions were the lowest ranked missions of the six, particularly after cost was taken into account. We note that there was almost no discrimination between the missions on a purely scientific basis (see Table 2), except when cost reasonableness (part of Criterion C) was taken into account (Table 2) and when programmatic considerations of balance and context were factored in (the ranking in Table 3). The SR2016 panel regarded both of those missions as highly scientifically valuable and productive, and here would like to identify the strongest cases for continuing both of those missions.

The case for Fermi

The Gamma-ray Burst Monitor, with its nearly all-sky coverage arguably provides the scientific community's best hope of capturing a simultaneous electromagnetic signature of a gravitational-wave event. The recent discovery of a gravitational-wave signature from a black-hole / black-hole merger puts this capability into dramatic relief. Furthermore, Fermi represents the only significant access to three decades of the GeV gamma-ray sky for many years to come. The SR2016 panel ranked the Fermi Large Area Telescope (LAT) lower than the GBM because it is much less likely to be a critical element in locating LIGO/VIRGO events, and while diffuse gamma-ray targets such as the dark matter searches are interesting, the main gains in signal to noise have come from the excellent progress in data processing as opposed to yields achieved by adding to the data over the next two years. On the other hand, if the operation of the LAT can be maintained into the era when the Cherenkov Telescope Array is operating, it could provide the additional spectral and temporal coverage essential to understanding a huge number of new TeV sources, which are mostly variable. The impact of reduced funding for operations is magnified for Fermi with its longer lifetime. (Fermi can continue for up to a dozen years.) The permanent loss of an instrument is devastating when compared to the potential scientific yields enabled by its long natural lifespan.

The case for Spitzer

The SR2016 panel identified that the strongest scientific case for Spitzer is its value in JWST-preparatory science. Spitzer has demonstrated its superb capability in finding high redshift ($z>7$) galaxies when Spitzer long-wavelength measurements are combined with Hubble Space Telescope observations of the same galaxies. It is also superb at finding high redshift clusters of galaxies ($z>1.5$-2) and characterizing exoplanet transits, as well as other JWST-relevant activities. There is certainly a cost-benefit to utilizing a Spitzer resource to obtain significant savings in terms of JWST observing time and timely early mission results. With a 5-10 year limited mission, the cost per observing hour on JWST is substantial. Making the JWST mission more efficient leverages the billions invested in JWST, and will allow JWST to achieve its maximum scientific potential. The Spitzer microlensing campaigns also provide science of direct relevance to the WFIRST mission. Continuing Spitzer Space Telescope operations support therefore has value to multiple NASA Astrophysics programs, a consideration should the Senior Review funding wedge prove inadequate.

Prioritized Program Reductions if Necessary

In the likely case of a financially-constrained scenario, the SR2016 panel prioritized an order of reductions that has been judged to maximize the science of the remaining portfolio. Such cuts should be approached and taken only as necessary to deal with budget realities. Any of these cuts have severe scientific and programmatic costs, as the elimination of a capability or resource affects the scientific productivity not only of the direct mission, but of other missions in NASA astrophysics or in the US astronomical portfolio of assets on the ground. The SR2016 panel has placed these reductions in order of scientific priority, from the least scientific impact to the most severe.

1. No overguides (Overguides to be cut in reverse order of scientific priority, which was described previously in this report).
2. Reduce the operating cost of Spitzer and Fermi in FY17 by up to $3.5-4.0 M each, including possibly reducing GO/GI funding.
3. Further reduce Spitzer total costs (without shutdown).
4. Further reduce Fermi total costs, maintaining GBM (without shutdown).

Individual Mission Evaluations

The six individual mission reports are provided in the following pages in alphabetical order: Fermi, K2, NuSTAR, Spitzer, Swift, XMM.

Fermi

SUMMARY OF MISSION AND PROPOSAL

Fermi is a gamma ray mission with two instruments: the Large Area Telescope (LAT, 20 MeV - 300 GeV) and the Gamma-ray Burst Monitor (GBM, 10 keV - 30 MeV). Fermi has the largest field of view of NASA's astrophysics missions, and with its high-cadence survey, temporal resolution and bandpass, is well suited for time-domain and multi-messenger astrophysics. Fermi was launched in 2008 and is now in its eighth year of operation. The Fermi team proposes to continue the operations for the next four years with a largely flat budget for NASA between $17M and $18M per year. Owing to the reduced funding of Fermi by the Department of Energy (DOE), the proposed flat NASA budget corresponds to a substantially reduced overall funding level.

CRITERION A: SCIENTIFIC MERIT

Fermi continues to be highly productive eight years after launch, as evidenced by a vigorous publication rate, highly cited papers and an oversubscribed general investigator program. Recent revisions in ground processing software have improved detection efficiency at low energies and source localization at both low and high energies. Scientific highlights in the past two years include the worldwide best constraints on the WIMP dark matter annihilation cross-section, the establishment of Galactic novae as an important class of gamma-ray emitters, and the possible detection of a binary supermassive black hole system. Among the most exciting prospects for the proposal period is Fermi's potential role in confirming and identifying gravitational wave sources detected by Advanced LIGO via temporal coincidences and refined positions from its Gamma-Ray Burst Monitor (GBM). Fermi's discovery of significant numbers of millisecond pulsars also enhances the Pulsar Timing Array's capability to detect gravitational radiation. Also tantalizing is Fermi's potential to detect gamma-rays from neutrino sources detected by Ice Cube. There will be substantial synergy with the Cherenkov Telescope Array (CTA) – even though the latter will still need several years to achieve a sensitivity surpassing that of the current experiments. Source population and light curve studies both benefit from continued observations owing to the increased depth and longer time baselines provided by continued observations, respectively. Fermi's all-sky coverage benefits the studies of time variable sources like blazars and gamma-ray binaries together with ground-based and space-borne observatories (e.g. NuSTAR, Swift). Furthermore, there are likely scientific synergies with the future (early 2017) mission Neutron Star Interior Composition Explorer (NICER), an International Space Station payload that will monitor neutron stars in the 0.2 - 12 keV band.

As Fermi has observed almost the entire sky for approximately 8 years, the available fractional improvement in upper limits on the emission from steady sources (e.g. dark matter) necessarily declines with each subsequent year of operations. The number of gravitational wave counterparts that can be detected with the Fermi GBM may be low, and GBM error regions tend to be large. A significant proportion of the anticipated improvement in its sensitivity to signatures of annihilating or decaying dark matter particles will accrue from the discovery of new dwarf spheroidal galaxies; most of the signal will come from summing the past data stream at the newly discovered locations, even with future Fermi observations. While gamma-ray studies of high-energy particle population deliver interesting phenomenological information, some of the observations are unlikely to unambiguously constrain the underlying physics (e.g. provide hard constraints on the neutron star matter equation of state, identify the mechanism launching jets of Active Galactic Nuclei). The SR2016 panel concluded the highest scientific value for continuing Fermi operations is therefore monitoring the transient gamma-ray sky.

CRITERION B: RELEVANCE AND RESPONSIVENESS

Fermi is highly relevant to the research objectives and focus areas of the Science Mission Directorate, and clearly relevant to the goals of the Astrophysics Division. Fermi is an important component of NASA's capabilities for time domain astrophysics, an area recognized by the 2010 Decadal survey as a critical new discovery domain. Fermi is playing a role in two priority science areas established by the Decadal: Fermi's gamma-ray burst (GRB) studies contribute to 'searches for the first stars, galaxies and black holes'; and Fermi's studies of dark matter, jets, cosmic rays, neutron stars and black holes advance our understanding of the 'fundamental physics of the Universe' and the end-points of stellar evolution. Fermi directly addresses goals of the SMD Science Plan to 'probe the origin and destiny of our Universe, including the nature of black holes, dark energy, dark matter and gravity', and to 'explore the origin and evolution of the galaxies, stars and planets that make up our Universe.'

The mission has been quite successful in addressing the science objectives specified by the 2014 Senior Review. The Fermi GBM team has partnered with LIGO to develop machinery to search LIGO data for sub-threshold GBM events, and has actually published a GBM event contemporaneous and coincident with (though not necessarily associated with) LIGO's first reported gravitational wave event. Fermi monitored the Galactic Center during the passage of the G2 object in 2014, though, like other missions, it did not detect significant high-energy emission attributable to G2. Improvements to the data pipeline showed the earlier suggestion of a 130 GeV line from the Galactic Center was statistically insignificant, and observations of known dwarf spheroidal galaxies provide increasingly strong evidence that the diffuse 1-10 GeV Galactic Center emission is unlikely to be due to dark matter annihilation. Finally, the spectral energy distribution and edge morphology of the Fermi bubbles were examined in greater depth, although available data do not distinguish between hadronic and leptonic emission models for the bubbles. Good progress has also been made on the operational objectives. "Pass 8" processing has been completed, and provides a significant sensitivity enhancement. An observing mode biased toward observations of the Galactic Center was implemented. Some improvement in the rate of short GRB detection has been achieved, and the latency of GBM triggers has been significantly improved through automation of the ground analysis. Although the new Pass 8 ground processing improves the effective area at all energies and in particular, at the lowest and highest energies. Large systematic errors do not allow full advantage of this improvement at the lower energy end. The 2014 Senior Review also recommended that the Fermi team plan for a budget reduction after FY16. In part for reasons discussed in the following section, this budget reduction has not been possible.

CRITERION C: TECHNICAL CAPABILITY AND COST REASONABLENESS

Fermi ground data analysis is highly complex and the team's successful completion of the new Pass 8 processing pipeline within the available resources is commendable. The observatory and instruments are healthy. With the completion of Pass 8 and other long-term spacecraft engineering initiatives (e.g., development of reduced- and zero-reaction wheel observing modes), some reduction in operations costs (per the Senior Review 2014 recommendation) would have been expected. However, the proposed Fermi budget includes no such reduction. The panel recognizes that the anticipated reduction of the Department of Energy (DOE) funding after FY2018 requires a major restructuring of Fermi ground operations and the preparation for this transition may be expected to require additional resources. This reorganization will shift most responsibilities for LAT instrument support from the SLAC National Accelerator Laboratory at Stanford to the Goddard Space Flight Center, a change that, in the panel’s view, is likely to present a major challenge to Fermi operations.

OVERALL ASSESSMENT

Fermi, the only space born GeV gamma-ray astrophysics observatory world wide, has exciting potential for multi-messenger astrophysics and provides unmatched capabilities for time domain astronomy and astroparticle physics. It thus plays an important role in NASA’s mission portfolio. In view of the absence of another MeV/GeV observatory in the foreseeable future, substantial cost reductions of the annual budget are highly desirable when compared to potential termination, as cost economies could enable NASA to support Fermi for an extended period of time. Should there be a NASA budget shortfall requiring reductions of the Fermi support, it should be emphasized that maintaining Fermi’s GBM is a particularly high priority as it may become a crucial player in the search for electromagnetic counterparts of gravitational wave events. The SR2016 panel identified the planned reduction of the DOE support for the mission as a concern; the transition presents a significant challenge to smooth acquisition, calibration and distribution of the data, as well as possible added cost for NASA.

K2

SUMMARY OF MISSION AND PROPOSAL

The K2 mission is an extension of the Kepler mission whose primary goal was to determine the fraction of planets - especially in the habitable zone - around stars. Kepler discovered thousands of transiting exoplanets through extremely precise optical photometry. The mission proposed to continue its cadence of observing campaigns along the ecliptic plane at a total cost of $10.4M (2017) and $8.9M (2018), of which about $2M per year goes to its GO program.

CRITERION A: SCIENTIFIC MERIT

The scientific results of K2 cover many areas in astrophysics, and we highlight a few here.

K2 has discovered new and unusual exoplanets, such as “hot super-earths” and “hot neptunes,” new types of exoplanets prime for study with transit spectroscopy and in synergy with a number of upcoming new missions. The team expects that 500 to 1000 transiting and several microlensing planets will be found in the next two years of the mission. K2 has also discovered potentially habitable rocky exoplanets as targets for JWST and ground-based large telescopes and as precursor science for WFIRST. Furthermore, K2 has enabled advances in our understanding of the lives of stars. K2 conducts asteroseismology of stars throughout their evolution. For example, the evolution of red giants into the next phase of their lives is studied in unprecedented detail, including uniquely determining the tilt of the star’s rotation axis. These observations contribute to an area of stellar astrophysics which has been poorly understood observationally and theoretically. New results also address magnetic field transport and convection in white dwarfs. K2’s study of close binary stars reveals the role of the common envelope evolution in producing rapidly rotating white dwarfs. K2 has achieved, additionally, dramatic observations of pre-explosion supernova light curves to study their early development, to observe directly the shock breakout and to determine the progenitor’s radius for Type II supernovae. For Type Ia, at least in one instance, conclusive evidence has been obtained that the progenitor is a white dwarf - white dwarf binary. Eighteen supernovae have already been observed in this manner and more are expected. K2 has also conducted observations of solar system objects such as known trans-Neptunian objects and their rotation periods, along with fascinating new studies of Neptune’s atmosphere.

The mission team has shown an effective, active strategy in recruiting people from outside the original Kepler Community who enhance scientific returns. Furthermore, the results from K2 feed into future missions such as TESS, JWST, Plato and WFIRST as well as ground-based observatories.

The MAST archival system makes the data extremely accessible and immediately available. One area the committee recognized that could be an additional source of unanticipated science would be to make the short-cadence data available in calibrated light curves. If this cannot be accomplished within the available budget, the mission should explore whether the community could provide existing software and documentation that would facilitate this. The committee appreciates that calibration of this data is extremely complex, but the added easy availability of at least quick-look light curves is potentially of great importance for enabling time domain science. Calibration techniques that have already been used for published data could be documented and related code provided through the archive.

CRITERION B: RELEVANCE AND RESPONSIVENESS

The K2 proposal is very responsive to the SMD Science Plan and the Astro2010 Decadal Survey covering all areas of understanding the universe, its origins and exoplanets. The PMOs that were proposed in the 2014 Senior Review were substantially exceeded in every respect. No weaknesses in this category were identified.

CRITERION C: TECHNICAL CAPABILITY AND COST REASONABLENESS

K2 cost efficiency was found to be very effective with an excellent operation model and rapid distribution of data. Current operating costs are reasonable. While the new science teams are still "ramping up" their efforts, the administrative cost of the GO program is high at over 25% of the total grant funds supplied.

The spacecraft is in good health. Even though the mission suffered the loss of two reaction wheels, the new mode of operation has maintained the photometric precision for most objects, and improvements in the efficiency of fuel consumption allows for at least two more years of observations. The spacecraft has experienced only one fault into "Safe Mode" over the past two years, despite a conservative estimate in operational planning that such events would happen twice a year. The team has additional ideas to use the solar wind and one of the antennae to improve efficiency and possibly allow continued work into FY19. This is largely dependent on fuel consumption. The committee notes that even though the mission is achieving a level of fuel consumption that is less than even the most optimistic scenario, the planning should continue to consider this to be optimistic and should not assume in future planning that there will not be a higher cadence of "Safe Mode" triggers as the spacecraft ages.

OVERALL ASSESSMENT

K2 represents an ideal example of why NASA continues to operate missions after their prime phase has been completed. This particular mission, which had a spectacular prime phase, has now been cleverly repurposed to cover a far wider range of science than originally proposed, and in many areas of astrophysics it is making significant cutting-edge breakthroughs and discoveries. The prime mission provided a tremendous advance in understanding the range and statistics of the general population of planets orbiting stars within our Galaxy. Due to the loss of some pointing capabilities toward the end of the prime mission, the team devised a clever use of the spacecraft to achieve nearly identical photometric precision and pointing but only for fields along the ecliptic. In the previous senior review, this new capability was only tested at the level where the committee was convinced it might work, without significant results to show. Now the team has exceeded all expectations. The SR2016 panel was so impressed with this mission that it is one of the two top missions, for multiple reasons. The slew of scientific results represents significant advances in many fields of astrophysics, not just exoplanet studies. It could be argued that K2 has already, and will continue, to contribute to broader science than during the prime mission. It is thus a perfect example of the purpose of mission extensions. Furthermore, with a very efficient GO program, the project includes worldwide participation covering every continent except Antarctica. The GO program is recognized as a major reason for the wealth of new scientific results.

The SR2016 panel recommends full funding of the completion of the K2 plan for the next two years.

NuSTAR

SUMMARY OF MISSION AND PROPOSAL

NuSTAR is the first focusing hard X-ray mission, with unprecedented sensitivity in the hard X-ray band (10-80 keV) and excellent sensitivity extending to energies as low as 3 keV. NuSTAR offers sub-arcminute imaging, excellent energy resolution (e.g. 0.4 keV Full Width Half Maximum at lower energies), and excellent timing without photon pile-up (pile-up occurs when photons from a bright source are arriving so quickly that the detection system has trouble distinguishing their arrival as single events, leading to challenges in analysis.) After a two-year PI and science team led period following its launch in 2012, NuSTAR started to transition towards a guest investigator led operation mode in 2015. The NuSTAR team proposes to continue operations for the next four years with an essentially constant budget of $7M per year. Commendably, the team identifies several potential under-guides as cost-saving options.

CRITERION A: SCIENTIFIC MERIT

NuSTAR's focusing hard X-ray optics provide unprecedented, unique and powerful imaging capability in the 3-80 keV band. The mission has made outstanding scientific progress in several areas. NuSTAR has resolved a significant fraction of the extragalactic hard cosmic X-ray background (CXB) and obtained interesting results on individual obscured AGN, revealing unexpectedly complex and variable obscuration. It has provided fascinating new insights into the strong gravity near black holes and neutron stars. A major breakthrough occurred with two independent measurements of the spin of the neutron star X-ray binary GX339-4. Impressive progress has been made in the accretion physics of AGN, wherein NuSTAR, together with X-ray observations by Swift, resolved a long-standing controversy on the interpretation of broad iron lines in AGN spectra by simultaneously measuring the iron lines near 7 keV and the accompanying, very broad, Compton reflection hump, which peaks at energies near 20 keV. It also obtained new constraints on the temperature, optical depth and size of the hot corona in AGN, supporting the "lamppost" model for the X-ray corona of the AGN Markarian 335. Particularly impressive also is the first measurement of the relativistic Lense-Thirring precession of the inner disk in the Galactic black hole binary H1743-322. NuSTAR has also provided new information on the physics of supernova explosions with its recently completed study of ^{44}Ti nuclear emission lines in a sample of young, bright supernova remnants. This program showed clear asymmetries and unexplained complexity in the distribution of different elements in core-collapse supernovae. In the case of SN1987A a fascinating redshift of the ^{44}Ti lines is found, indicating a strong kick of the putative neutron star towards us. Finally, NuSTAR has made excellent advances in the study of X-ray binary populations in nearby galaxies. A particularly beautiful result is the discovery of a hyper-luminous X-ray pulsar in the nearby galaxy M82, confirming the presence of super-Eddington accretion in at least some ultraluminous X-ray sources. This discovery may have important consequences for black hole growth over cosmological time scales. NuSTAR boasts an impressive record of additional discoveries in other fields, e.g. the unresolved hard X-ray emission in the Galactic Center region and its interpretation as Intermediate Polars, as well as the discovery of a high braking index for a young pulsar, possibly indicative of energy loss to gravitational waves.

NuSTAR has conducted productive joint observations with virtually every other high-energy instrument available, including Swift, Chandra, XMM, Suzaku, Integral and Fermi, as well as with Hubble and Spitzer. A particularly beautiful example of this synergy is the simultaneous XMM-Newton and NuSTAR observation of the luminous quasar PDS456. The two missions together discovered a massive outflow in this source, with a kinetic energy of 10^{44} erg/s, driven by its central supermassive black hole. Such outflows almost certainly play a fundamental role in galaxy evolution. Quantifying them is essential for a complete understanding of the development of galaxies over cosmic time. Almost every NuSTAR pointing is accompanied by an observation with Swift, so that the synergy between these two missions in achieving the discoveries discussed above is particularly striking.

NuSTAR is a relatively young mission. With a well-organized and productive science team, a competitive GO program in place, and a well-functioning observatory, NuSTAR will very likely continue to produce high-impact results during the proposal period. The mission will focus on three primary objectives in the near term. It will continue to study the growth of black holes over cosmic time. So far NuSTAR has resolved about 35% of the hard CXB. To achieve the goal of resolving 50% of the background, deeper observations are planned, in particular in the CANDELS fields. There is also a plan to cover larger solid angles in the future, as well as following up the BAT sample. This effort will be a 'legacy survey' and will be made public immediately.

NuSTAR also plans to continue its highly successful efforts to probe strong gravity and the behavior of matter under extreme conditions. These will be largely driven by the growing Guest Observer program and will concentrate on black hole spin measurements, high-energy transients, and X-ray binaries. In addition, a particular legacy program is focused on the activity of SgrA*.

Population studies of compact objects in the Milky Way and nearby galaxies will be a new focus for the proposal period. These are motivated by exciting discoveries made in the field of resolved X-ray binaries in nearby galaxies and will include further legacy observations.

Overall the mission has a strong record with a growing number of publications (160), and its GO program is quite competitive. The project is now in the transition from a PI-led program with significant community input to one in which at least 50% of the observing time is awarded competitively. The second AO is just starting, and the SR2016 panel believes the GO program is likely to be an important factor in maintaining the mission's excellent scientific productivity. The mission is considering expanding the GO program to include very large programs, taking time as required from team Legacy programs; the SR2016 panel encourages this step.

NuSTAR conducts Target of Opportunity observations (ToOs) from PI discretionary time, and data from these are given a 6 month exclusive use period, unlike some other NASA missions. The SR2016 panel recommends that the mission consider making ToO data public immediately. NuSTAR data products are designed to follow HEASARC data standards for FTOOLS and CALDB, which are easily usable. The distribution time meets the mission requirement (11.5 days vs. 14 days). As of Sept 2015, all data through March 15 are in the archive.

CRITERION B: RELEVANCE AND RESPONSIVENESS

NuSTAR is highly relevant to the objectives and focus areas described in the SMD Science Plan and to the goals of the Astrophysics Division. Key questions from the NWNH Decadal Survey are addressed, including “How do black holes grow and influence their surroundings?” The same is true for PCOS key questions: test General Relativity; understand the formation and growth of massive BH and their role in galaxy evolution; explore the behavior of matter and energy in extreme environments. NuSTAR remains at the forefront of several of these fundamental areas.

NuSTAR has been very successful in addressing and achieving the Prioritized Mission Objectives set for it by the 2014 Senior review: There has been excellent progress on PMO2 (probing the nature of strong gravity and matter under extreme conditions) and PMO3 (probing supernova physics by measuring the spatial distribution of ^{44}Ti in a sample of young SNR). PMO2 continues and PMO3 has been concluded. Solid progress has also been achieved on PMO1 (BH growth) with the publication of the first catalogs and synthesis papers on number counts and the X-ray luminosity function, though resolving >50% of the hard XRB remains a major challenge. Work toward PMO1 will therefore continue with high priority in the proposal period.

There were no formal weaknesses in the 2014 Senior Review, but some programmatic recommendations were made. In particular, NuSTAR achieved a factor of four reduction in the cost of administering its GO program (from $1.7M to $400k). While this economy is commendable, the SR2016 panel notes that this cost is still slightly above that achieved by other missions, and urges NuSTAR to seek additional savings in this area. The 2016 panel was in particular encouraged to evaluate NuSTAR in the light of the upcoming Astro-H mission (recently launched successfully and named Hitomi). The NuSTAR proposal addressed the differences with Hitomi very well and the SR2016 panel regards the two missions as highly complementary.

CRITERION C: TECHNICAL CAPABILITY AND COST REASONABLENESS

NuSTAR has improved efficiency significantly, allowing a reduction in overall mission costs by 12%, while at the same time increasing GO program funding from $1.5M to $2M.

The mission is in excellent health and has experienced no performance degradation since launch. The projected life of the mission, limited by orbit altitude and solar activity, is ten years. The SSL operations model is well-suited to a SMEX-class mission, also making effective use of young team members. Achieving an observing efficiency of 55% in low-earth orbit is remarkable!

The overall budget at $7M per year appears to be reasonable. The project is commended for offering budget reduction options of up to $600,000 in its proposal. The mission’s grants administration costs, at about 19% of grants disbursed, appear to be slightly higher than for other missions.

OVERALL ASSESSMENT

NuSTAR’s unique hard X-ray imaging capabilities have been deployed to produce ground-breaking science during its first four years of operations. Future mission objectives are well matched to instrument capabilities, and efficient operations have enabled an expansion of the GO program and a reduction of overall mission costs. NuSTAR is a highly productive mission in full command of its original capabilities. In particular in combination with other X-ray missions NuSTAR is a superb tool allowing us to address scientific questions inaccessible to either mission on its own. Funding should continue at the requested level. The panel recommends to distribute all Target of Opportunity data without a proprietary period.

Spitzer

SUMMARY OF MISSION AND PROPOSAL

The Spitzer Space Telescope mission proposes to continue for two more years of operations; with the launch of JWST at the start of FY19, the mission will shut down. The level of operations is chosen to provide full support for a broad mix of creative scientific programs, proposed by the GO community and selected by peer review. The request level for FY17 is $15.25 million.

During this warm mission phase, the IRAC instrument offers imaging of high photometric quality at 3.6 and 4.5 microns. A particular strength highlighted in the proposal is the ability to carry out critical precursor science that will allow much more efficient initial use of JWST. Examples include refinement of transit timings of up to several hours from K2 discoveries of rocky planets in the habitable zone, detection of high redshift galaxies and substantial reduction of uncertainties in photometric redshifts for newly discovered galaxies with redshifts greater than 7 beyond the reach of optical surveys. The Spitzer microlensing campaigns provide another path to characterize exoplanetary systems as well as a preview of techniques and results relevant to WFIRST science. An incredibly rich array of solar system, Galactic and extragalactic science with increasing new discoveries continue to characterize the scientific impact of this mission.

CRITERION A: SCIENTIFIC MERIT

The Spitzer Space Telescope has been a tremendously successful observatory that has achieved landmark results across the range of astronomical topics. For the past few years it has worked in a more limited capacity, utilizing only the bluer channels of the IRAC instrument in what is termed the *warm mission*. The observatory has partially balanced this loss of capability with a range of new observing modes, primarily focusing on longer research programs. This has resulted in Spitzer continuing to produce high impact results during the extended mission phase.

The spacecraft is highly reliable and offers unique sensitivity at 3.6 and 4.5 microns, not to be duplicated until JWST is in orbit. Its distant (sun trailing) orbital position permits a long, uninterrupted stare mode, of particular value for exoplanet observations and characterization. Within the compelling broad range of scientific programs of SST, its strong scientific potential for precursor science for JWST, in the fields of exoplanets and the high-redshift Universe emerge as a critical capability for the duration of lifetime. To provide specific examples of important JWST precursor science, two applications are illustrated, one in the exoplanet regime and another for high redshift science. Extremely low amplitude follow-up light curves for rocky planets in the Habitable zone currently cannot be obtained elsewhere. An observation spaced in time reduces uncertainties in transit timings through follow-up of these small K2-discovered exoplanet systems by up to several hours, allowing for much more efficient JWST observing of their transits. These planets will be among the first targets for JWST. Although bigger planets - depending on planet to star size - can be observed from the ground, the small rocky planets in the Habitable Zone cannot. The upcoming TESS mission will probe a different parameter space of potentially habitable planets, complementing the K2/Spitzer mission targets for JWST. Therefore, the combination of the Spitzer and K2 missions provides a strong synergy for identifying exoplanet targets for JWST.

Spitzer observations are also critical for finding high redshift galaxies and for narrowing the range of uncertainties in photometric redshift for the highest redshift candidates (the GREATS survey of the GOODS fields is expected to identify more than 200 galaxies at $7 < z < 10$). This work highlights a key synergy with Hubble Space Telescope. Galaxies in that redshift range can be nearly invisible at shorter wavelengths, requiring initial deep near-IR and visible light imaging with HST to provide stringent upper limits on emission from light at short wavelengths and significant detections of the emitted continuum at wavelengths longward of the redshifted Lyman break, which defines a very strong feature in galaxy spectra. Spitzer Space Telescope detections in the two IRAC bands then allow definitive fitting of spectral energy distributions for confirmation and photometric redshifts. The brightest gravitationally lensed objects can then get preliminary grism spectra from HST as well. Determining the distribution of masses and star formation rates, along with estimating the incidence of AGN ionization, is a critical next step in understanding galaxy formation and reionization in this highest observed redshift range. Development of a list of prime targets for early science with JWST is invaluable for efficient use of the spacecraft during its limited cryogenic lifetime. The preliminary observations of these highest known redshift objects are also highly valuable for refinement of photo-z methodology and relevant SED modeling for this currently poorly understood population.

A science topic of direct relevance for JWST and WFIRST is microlensing of stars in the Galaxy. Caustic crossings allow the detection of associated planets, even Earth-like planets in the habitable zones of rather distant stars. Spitzer Space Telescope observations provide two major advantages. The small timing difference arising from observing the microlensed star simultaneously with ground-based telescopes allows astronomers to break the degeneracy between lensing mass and distance in order to get the mass of the lensing star and therefore the mass of its planet and orbit information. In addition, the campaigns are conducted in fields with the highest likelihood for microlensing events, through the bulge near the Galactic Center, such as Baade's Window. IR capability significantly reduces the impact of low-latitude extinction. The distant orbit of the spacecraft allows long-duration time coverage, for which the mission team provides an extra level of intensive support.

Outside of JWST and WFIRST precursor science, Spitzer continues to generate high impact results over a broad range of topics. Observations of Neptune, Pluto, TNOs and asteroids also make Spitzer science very relevant to characterize Solar System objects and continue to generate surprises. In cosmology, IRAC photometry measurements are critical to the derivation of redshift estimates, stellar masses for the most massive galaxy clusters, and, ultimately, constraints on the initial density perturbation spectrum and on the growth of large scale structure. A new focus on the population of NIR transients, particularly those of luminosities intermediate between novae and supernovae, is identifying new classes of systems. An incredibly rich array of solar system, Galactic and extragalactic science with increasing new discoveries continue to characterize the scientific impact of the mission.

The level of user support and value of the archive remain extremely high for the community. The mission provides substantial user support, which allows a wide range of science, including evolving programs. This quality might be expected, given the Great Observatory heritage, but the pipeline processing has improved over time and the support staff continue to develop new observing modes even after substantial staffing reductions.

As discussed, the Spitzer Space Telescope has direct synergies with HST, K2, and the upcoming TESS, JWST and WFIRST. As such, it is not only enhancing the science done with current NASA facilities, but also that will be done with future missions, especially optimizing early science observations for JWST and WFIRST.

While high-redshift science will ultimately take a giant leap forward with JWST, the proposed precursor observations are critical for a strong and efficient start with JWST. The proposal submission rate is somewhat lower than some other extended missions, but this difference may be the result of a larger minimum proposal size for new Spitzer projects.

CRITERION B: RELEVANCE AND RESPONSIVENESS

The Spitzer Space Telescope allocates most of its observing time to exoplanet research and to the distant universe and cosmology. Its emphasis on exoplanet research and the applicability of its observations to the census of earth-like planets is in direct support of one of the three major NWNH goals. The critical application of its observations to Early Universe studies addresses a second one. This mission is directly aligned with the major stated SMD scientific priorities.

The Prioritized Mission Objectives from 2014 were well addressed with the operations, data collection, user support, and data archive and accessibility over the last two years of operation. The team has addressed the PMOs from the 2014 Senior Review and trimmed staffing level. The staffing is 46% lower than at the start of warm mission. There have been significant reductions in costs during the evolution from the cryo to the warm mission, and even during the warm mission.

CRITERION C: TECHNICAL CAPABILITY AND COST REASONABLENESS

The operations model emphasizes user support, full archiving for public access, and a proposal-driven suite of diverse science programs. That model has been made cost efficient for that style, in the context of the discussion above, with the choice to maximize science return.

The spacecraft health seems solid, and the operations plan continues with no significant increased risk from that of previous cycles. In the case of (minor) anomalies, JPL has access to key high-level engineering staff on an as-needed basis. The new operating mode of smaller sun angle for downlinks is asserted to be low risk, with the straightforward approach of immediate recharging after the downlink has completed.

A concern in the 2014 Senior Review report was the high cost of this mission relative to others, and the team did not identify any further cost savings. The fundamental mode of full user support incurs a certain level of cost, with a high scientific return. Long stare campaigns, such as those for microlensing and exoplanet transit monitoring require a significantly heightened level of support. Some of the enhanced cost could also be the heritage of operational complexity inherent in the initial design for a great observatory.

The mission has managed to achieve some additional cost savings, while continuing to fully support the community-assessed top ranked science. There is no current software development staff, and much of the

JPL-based technical staff is shared with other missions. The mission will be closed out at the end of FY18, at the launch of JWST.

OVERALL ASSESSMENT

By having a vigorous GO program, the mission has been able to support the best new ideas from the community in a way that has maximized new discovery potential. Spitzer Space Telescope observations are key to high impact results in areas ranging from exoplanets to the most distant Universe. The mission meets key SMD priorities in support of NWNH scientific objectives, and management choices over the period since the last Senior Review were responsive to the stated Primary Mission Objectives. Although this mission is somewhat higher cost than others, the mode of strong user support has enabled the very diverse suite of investigations that has made the mission productive and high impact.

The impending launch of JWST creates positive and negative factors in evaluating this mission programmatically. The capabilities of JWST will vastly exceed those of the current SST mission, by design, so there will be dramatic and immediate gains in the quality, depth, and quantity of data that can be obtained on the topics currently under investigation. JWST is a high cost mission with a limited lifetime, so precursor investigations that can lead to initial high-impact results and higher scientific mission efficiency, such as those proposed for the next two years of SST operations, have considerable value. It is also evident that large and long programs that SST can execute over the next two years will be much more difficult to carry out initially in the highly competitive regime of early JWST science. The panel believes that the diversity and quality of the programs possible with SST would be attractive to multiple NASA programs in support of key mission objectives.

Swift

SUMMARY OF MISSION AND PROPOSAL

Swift carries three complementary instruments: a pointed X-ray telescope (XRT, 0.3-10 keV), the large field of view Burst Alert Telescope (BAT, 15-350 keV), and the UltraViolet and Optical Telescope (UVOT, 170-650 nm). The combination of these instruments together with Swift's rapid slewing capability, extremely flexible scheduling, vigorous guest observer program, and its truly spectacular Target of Opportunity service makes it an extremely successful mission. Swift's capability to find and study transient events like Gamma-Ray Bursts (GRB) and their afterglows, supernova explosions, and tidal disruption events continues to deliver cutting-edge results with implications for fundamental physics, stellar physics, black hole physics, high-energy astrophysics, and cosmology. The Swift team proposes to continue the operations for the next four years with a largely flat budget for NASA of about $6M per year. Four targeted over-guides were proposed to increase the science return from the mission (see recommendations on these over-guides below).

CRITERION A: SCIENTIFIC MERIT

Although the Swift mission was initially primarily observing Gamma-Ray Bursts (GRBs), and they continue to play an important role in the mission portfolio, the primary emphasis has shifted to Target of Opportunity (ToO) observations, with about twenty five per day being executed. Its multi-wavelength suite of instruments combined with its rapid response capability is unique among NASA missions. The strong proposal demand and high publication rates attest to the high community interest. The science results cover a broad range of topics and include such high-return results as the recent detection of a UV pulse from a young Type Ia supernova, the discovery of a luminous supernova from an ultra-long GRB, the observations of a near infrared transient following the Swift detection and localization of GRB 130603B consistent with the kilonova hypothesis, the observation of an X-ray scattering dust halo around the black hole X-ray binary V404 Cyg, new constraints on the structure of the inner accretion flow of the Seyfert 1 galaxy NGC 5548 based on X-ray reverberation observations, and the detection of the GRB 140515A at a high redshift of $z=6.33$. The expansion of the scientific breadth of Swift is exhibited by observations of transits of extrasolar planets in X-ray and UV informing us about stellar irradiation and chromospheric activity.

The Swift team presents a compelling science program for the next 4 years. The program includes the search for electromagnetic counterparts of gravitational waves through follow-ups of advanced LIGO detections, which have very large "error boxes" describing the regions of the sky where the source of gravitational waves could be located. Swift could rapidly tile large areas of the sky, but the probability for a successful Swift follow-up would be greatly increased if Fermi can help find the gravitational wave event by localizing a simultaneous gamma-ray event in a smaller sky region.

Swift could verify the connection between "short-hard" GRBs and neutron-star mergers through observations of near-infrared kilonova emission from the neutron-rich radioactive ejecta produced in neutron star/neutron star merger events. Swift will scrutinize the structure of the inner engines and jets of active galactic nuclei through various types of X-ray and multiwavelength observations including, but not limited to, spectral and timing (reverberation) studies. The Swift program includes probing the high-redshift universe and the epoch of reionization by detecting high-redshift GRBs and observing spectral features in their afterglow emission. Swift will use its time domain capabilities to observe objects from ongoing and future surveys such as the Zwicky Transient Factory. The 11-year point-source catalog will be a valuable addition for the community. Swift creates and benefits from synergy with NASA's, ESA's, JAXA's, and ISRO's fleet of astrophysics missions.

CRITERION B: RELEVANCE AND RESPONSIVENESS

Swift addresses the first "Science Objective" and three out of the five "Frontier Discovery Areas" in the 2010 decadal survey as well as two of the three "astrophysics imperatives" in the 2014 SMD Science Plan. For example, Swift's studies of GRBs elucidate the endpoints of stellar evolution, the formation of black holes, potential sources of gravitational waves, the equation of state of neutron star matter, and the high-redshift Universe. Swift made good progress towards the PMOs described in the 2014 Senior Review proposal. Particularly successful were discoveries in the area of time domain astronomy leading to several high-impact results including the discovery of ultra- long GRBs, the detection of a UV pulse from a SN Ia, X-ray reverberation results measuring the size of the accretion disk of the Seyfert galaxy NGC 5548, and the discovery of a tidal disruption event. The detection of elevated NIR afterglow fluxes of a short GRB have strengthened the case for binary neutron star mergers as the progenitors of short GRBs. More GRBs have been found at redshifts of 6-7, and high-redshift follow-up capabilities are improving. The supernova Ia program has been very successful, and is contributing useful constraints on the evolution of UV-bright supernovae. Swift is a partner on almost all NuSTAR observations, increasing the wavelength coverage (to low energy X-rays and UV) and the astrometric precision of NuSTAR. Swift also regularly combines with Chandra and XMM-Newton in joint programs (providing trigger and/or followup observations), and has been invaluable in following up on discoveries by Fermi. The team implemented several of the initiatives discussed in the 2014 Senior Review even though it did not receive additional funds for those initiatives. Good progress has also been made on several of their proposed initiatives (automation, a pipeline for XRT serendipitous discoveries, a survey of nearby galaxies, a plan for BAT triggers and a Key Initiative Project), even though none were funded.

CRITERION C: TECHNICAL CAPABILITY AND COST REASONABLENESS

Swift operations are lean and very efficient, with a modest number of FTEs charged to NASA despite the fast response times and voluminous scheduling required by the GI and ToO programs. The team is leveraging significant in-kind contributions from international partners (Italy, UK and Denmark). The data are archived by HEASARC with no proprietary period, quick look products are available in hours, final data in about a week and prompt GRB alert notices are issued, giving easy data access to the community. The team is steadily developing new capabilities to enhance scientific contributions. Examples of this are the automatic tiling of XRT and UVOT pointings to cover the large error circles of triggers from Fermi and upcoming facilities such as HAWC, Ice Cube, and LIGO, and the provision of sub-threshold BAT triggers to the community for multi-messenger coincidence detections. The latter are currently being upgraded to real-time notification. The spacecraft and all instruments are in good operational health, with no obvious degradation except for the expected gradual loss of energy resolution in the XRT CCD due to radiation damage and small sensitivity degradation in the UVOT. Active temperature control of the CCD was lost at the beginning of the mission, but passive control techniques were developed that still allow un-degraded operation of the XRT more than 99% of the time. There have been multiple failures in the BAT heat pipe controllers, but they are confident they can fully maintain BAT performance even if the remaining controller fails. So at this point there are no hardware issues on the horizon that would prevent normal operation for the foreseeable future.

The overguide requests are for 1) further automation, 2) increased GI funding for rare ToOs, SMC and galactic plane surveys and 3) new operating modes for UVOT that will provide time-tag photons, increased photometric precision and the pipeline identification of serendipitous sources.

OVERALL ASSESSMENT

Swift gives impressive testimony for how much a mission can evolve during its life span and how much it can benefit from community involvement through vigorous target of opportunity and guest observer programs. The panel would like to see the highest ranked over-guide initiatives funded if possible. The "Automation for Rapid Response and Risk Reduction" has the highest priority of the SR2016 panel as it will add key capabilities for the search for gravitational wave counterparts. An enhancement of the extremely successful guest observer program would be desirable which could fund innovative instrumental initiatives, the SMC and galactic plane surveys, or other programs.

XMM-Newton

SUMMARY OF MISSION AND PROPOSAL

XMM-Newton is a fully operational Great-Observatory class X-ray observatory, launched in 1999 and operated by the European Space Agency. NASA participates in the mission by supporting the NASA Goddard Space Flight Center Guest Observer Facility, a guest observer program, and the US Reflection Grating Spectrometer Team. XMM-Newton carries three X-ray telescopes with sensitivity in the 0.2-12 keV energy band and an optical/UV telescope.

The XMM-Newton team requests a continuation of NASA support of US XMM investigators through GO funding program (currently $2M, which they propose to expand to $3M in order to support a larger fraction of the successful US proposers) and the amount of <$1M towards the maintenance of user support activities of the US Guest Observer Facility at Goddard Space Flight Center.

CRITERION A: SCIENTIFIC MERIT

The astronomical community continues to participate in and produce XMM science at a high rate. XMM science has been featured in over 760 refereed publications in the last two years, a publication rate comparable to Chandra (which has a higher dollar level of GO support), and with high impact papers (9 in Nature and Science). Continued oversubscription (5.6 in terms of requested time) also attests to the high community demand and interest. XMM's capabilities remain nearly identical to what they were at launch. XMM has a higher collecting area than Chandra, better spatial resolution than ASTRO-H (Hitomi), a wide complement of instruments (simultaneous X-ray, UV and optical imaging as well as X-ray spectra), and an extended orbit allowing long continuous observations that are not possible for the X-ray telescopes in lower Earth orbits. XMM's capabilities are highly complementary to the higher-energy spectroscopic coverage of NuSTAR, the higher spatial resolution of the Chandra X-ray Observatory, and the new, high resolution X-ray spectroscopy enabled by the recently launched Hitomi (ASTRO-H).

XMM-Newton observations enable scientific progress across a broad suite of scientific questions. Recent results include the discovery of a wide-angle, fast wind from a quasar hosted by a galaxy similar to the Milky Way. This discovery is relevant to studying mechanisms for quenching the formation of stars inside massive galaxies with AGN feedback. This latter observation was in concert with NuSTAR, which constrained the E>10 keV continuum well enough to allow the resolution of a P-Cygni profile around the Fe-K line, produced by a wind being expelled at high speed from the inner accretion disk. The high sensitivity and spatial resolution reveals what could be the so-called 'missing baryons' in hot filaments linking massive clusters of galaxies. The warm ionized gas of our own Milky Way halo has been detected and characterized via absorption line studies of X-ray binaries in the disk and active galactic nuclei. XMM enabled the spectroscopic study of gas being acquired by a supermassive black hole, fed by the tidal disruption of a star. Observations of a low-mass X-ray binary showed the transition to a millisecond pulsar, while flares from M-stars probe environments for exoplanets.

CRITERION B: RELEVANCE AND RESPONSIVENESS

Decadal survey priorities addressed by XMM observations include questions surrounding galaxy evolution and AGN feedback, investigations of how baryons behave in dark matter gravitational potentials, and tests of extreme gravity (black hole spin and the neutron star equation of state). XMM observations accomplish all 3 science goals of NASA's Science Mission Directorate by probing the nature of black holes and gamma-ray bursts, by conducting an indirect search for dark matter, by exploring the origin of galaxies (SgrA* lobes, galaxy halos), exoplanets (X-rays from brown dwarfs and M-star flares), and the inner structure of black hole accretion flows. The 2014 Senior Review recommended work on extended source analysis, which the XMM GOF completed, including incorporating software and Perl scripts with the XMM data analysis software distribution (SAS).

CRITERION C: TECHNICAL CAPABILITY AND COST REASONABLENESS

XMM is in excellent health. It has had strong continuing support from ESA and the European community. In the last extensions XMM-Newton and the Mars Express were identified as the most compelling on-going missions for ESA. The oversubscription rate in the last review was 5.6, with 432 proposals submitted. Its lifespan can potentially extend to 2028 and the planned launch of Athena+, because of the frugal usage of available fuel on board XMM.

Very slow degradation has been seen in the the carbon contamination of the detectors since launch. The maps of bad pixels and other detector features have remained quite stable (at less than 1.5% of the detector). The energy resolution of the solid state detectors has slowly gotten worse with time, widening by about 10% in FWHM in energy since 2000. XMM-Newton is very close to the same telescope and detector suite that was launched in 1999.

NASA has been supporting data analysis at the level of $2M annually for a subset of US observers who are XMM PIs; most recently, support has been limited to only PIs with A- and B-ranked targets. US observers who are co-Is of proposals with foreign PIs or proposals with only C-targets are not funded, which means that US investigators on major projects with foreign PIs are excluded from contributing to planning, analyses, or leading papers. The decision for how to allocate GO funds, however, is made at the NASA XMM Guest Observer Facility (GOF) together with its user community; other missions with similar levels of GO support divide their data analysis funding differently. Another $0.87 M has been used to support the work of the US GOF at Goddard Space Flight Center, towards data archiving, some software analysis task development and support, and grant management. Even though the US pays nothing towards the operations of XMM, US observers have enjoyed the access to compete for observing time on XMM. US proposers are very successful at winning time on XMM (40% of the accepted proposals for general observer time have US PIs and 80% have US PIs or CoIs). One of the more recent examples include a very large proposal for deep extragalactic X-ray imaging by a US PI for 1.38 Msec (10% of the available A and B time for this most recent cycle.)

OVERALL ASSESSMENT

XMM-Newton continues to produce Great Observatory level science unique to this mission and at a very productive rate. Since US funds none of the XMM-Newton operations, the continued US investment in this mission is the smallest in the SR2016 portfolio, and it is highly leveraged. The US partners with ESA in this mission by providing user support (including analysis software, scripts, data access) and data analysis funds for successful US proposers in a highly competitive annual international proposal competition. US analysis funds represent a significant contribution to the total support for XMM data analysis; US programs are a significant fraction of the XMM science schedule and scientific yield. A drop in GO support will threaten the overall scientific productivity of XMM. The SR2016 panel recommends funding XMM Newton at its current level.

The $1M augmentation of the GO funding would allow the US GOF to fund a larger fraction of the successful proposals, including US Co-Is with significant contributions in projects with foreign PIs. This augmentation would boost the scientific yield of US astronomers, but the SR2016 finds the full inline funding of the other SR missions to be of higher scientific priority than this augmentation.