



2012 Senior Review of Operating Missions in the NASA Astrophysics Division

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Introduction	3
Ranking the Missions:	
1. A Metrics Approach	4
2. A Category Approach	6
Missions in Alphabetical Order:	
1. The Chandra X-ray Observatory	8
2. The Fermi Gamma-ray Space Telescope	11
3. The Hubble Space Telescope	13
4. The Kepler Mission	16
5. The Planck Mission	20
6. The Suzaku Spacecraft Mission	23
7. The Swift Gamma-ray Burst Mission	25
8. The Warm Spitzer Space Telescope Mission	28
9. The XMM-Newton Mission	30
Acronyms	33

Introduction:

The goal of this Senior Review (SR) is to assist NASA to optimize the scientific productivity of its operating missions during their extended phase. This activity, which is the highest-level peer review, takes place every two years, with the last being held in April 2010. The Senior Review Committee (SRC) evaluates the anticipated science productivity of each mission over the next four years, focusing on the next two years. Budget guidance is given for FY 2013 and FY 2014, along with recommendations regarding whether missions should be terminated or extended beyond FY2014.

The charge states that the Senior Review should rank missions on a “science per dollar” basis, but after considerable discussion, the committee concluded that a simple ranking of this sort is not adequate. In place of a single ranking, we endeavor through both commentary and metrics to evaluate the value of the various missions, as discussed further below.

The value of a mission during its extended phase depends not only on the science that it might conduct, but also its place in the overall suite of future NASA missions. An active mission offering unique capabilities that will not be replaced for many years is considerably more valuable than a mission that will be shortly superseded. Aside from the anticipated launch of JWST at the end of this decade, there are no approved missions in most other wavebands. As a result, certain types of science will rely heavily on several of the missions reviewed here. This reality, along with the challenging fiscal situation facing Federal science agencies, places greater emphasis on utilizing existing missions wisely, as well as finding strategies for reducing costs while not sacrificing the most important capabilities.

Previous Senior Reviews led to the removal of funding for the weakest 10-20% of extended missions, some of which had partial instrument failures or significantly reduced capabilities. Missions that were ranked in the bottom third were often given an opportunity to improve their cost effectiveness and then evaluated in a subsequent Senior Review. This process is a sensible management approach when determining whether to terminate a mission that was constructed at considerable expense. However, this approach was no longer possible during the past two years as a result of sharp declines in the available budget for extended missions. Of the 11 missions considered in the 2010 Senior Review, nearly half were terminated or had funding withdrawn: RXTE, GALEX, INTEGRAL, WMAP, and WISE. The remaining six missions received strong evaluations (Chandra, Planck, Suzaku, Swift, Spitzer, XMM-Newton). In addition to these missions, three other missions are considered in this Senior Review: Kepler, Fermi (both in the transition from their prime to extended mission phase in FY2013-14), and HST. These nine missions comprise an extremely strong ensemble to enter the Senior Review process and we find that all are making very significant scientific contributions.

Ranking the Missions:

1. A Metrics Approach

A single number does not capture the value of a mission, which has many dimensions. The Senior Review Committee (SRC) discussed a number of different parameters by which missions can be measured and decided to use the six categories described in arbitrary order.

Discovery Space focuses on the range of observational space that can be probed as well as the number of astronomical objects or phenomena available to the instrument package; this element endeavors to measure the potential for the discovery of new astrophysical phenomena.

Long Term Scientific Impact assesses the unique potential for future science accomplishments of lasting value.

Publication Per Dollar: Different missions identified mission-related papers differently, and a “science per dollar” metric should probably include some evaluation of the scientific importance of papers. However we found the factor of 10-30 differences that exist are not significantly affected by methods used to select the papers, nor by using total citations instead of total papers.

Synergy corresponds to the value added of these observations to those of other observatories in addressing scientific issues; the frequency of such synergistic observations is also taken into account.

Critical Capability assesses the importance of the unique capabilities of the mission.

Health of the Science Program assesses whether adequate financial resources are provided to support the analysis of the science data. Unlike the above five criteria, this category only receives a “health” color. Green indicates satisfactory funding, while yellow and red indicate poor and critically low funding, respectively.

The evaluation of these categories, except for publications per dollar, is based on our anticipation of the science in the next few years. We note that programmatic issues, which may also be important criteria, were not considered. The numbering scheme is the one provided by the Astrophysics Division and it runs from 0-10, with larger numbers being better. We caution against averaging these five criteria, as the weighting to each category would differ depending upon the question posed.

MISSION	DISCOVERY SPACE	LONG TERM IMPACT	PUBLICATION/\$	SYNERGY	CRITICAL CAPABILITY	HEALTH OF SCIENCE PROGRAM (RYG)
CHANDRA	9	9.5	7	9	9.5	G
FERMI	7.5	7.5	7	8	9	G
HST	9.5	9.5	7	9.5	10	G
KEPLER	9	9	7.5	8	9.5	G
PLANCK	7	10	6	8.5	9.5	G
SPITZER	9	8	6.5	9	9.5	G
SUZAKU	8	8	10	7.5	9	R
SWIFT	9	9	9.5	10	9.5	Y
XMM	8	9	9.5	9	9	R

Mapping: Adjectival Ratings – Numerical Grades

E: $10.0 \geq S > 9.0$	E/VG: $9.0 \geq S > 8.0$
VG : $8.0 \geq S > 7.0$	VG/G: $7.0 \geq S > 6.0$
G: $6.0 \geq S > 5.0$	G/F: $5.0 \geq S > 4.0$
F: $4.0 \geq S > 3.0$	F/P: $3.0 \geq S > 2.0$
P: $2.0 \geq S \geq 0.0$	

Commentary on the Table

Discovery Space: Planck received a relatively low score (VG/G) because it is a highly targeted mission rather than an observatory designed to study a wide range of phenomena and because its data collection phase is largely complete. Fermi received a better, but still relatively lower score (VG), because despite covering a very wide range of the electromagnetic spectrum, leading to many discoveries, future observations are unlikely to lead to many new sources.

Publications per Dollar: This metric varied by about a factor of 40 among the missions. Using citations per dollar for papers from the same time period or using very different selection criteria for the papers changes the relative results by less than a factor of two and would not affect the ratings. The lowest scores were for Planck and Warm Spitzer, both of which are too new to expect useful publication records. The three highest scoring missions (Suzaku, Swift, and XMM) have publications per dollar approximately an order of magnitude greater than the others. This publication efficiency is primarily due to nearly all of the mission costs being borne by our foreign collaborators. Even increasing their total NASA funding by a factor of two without an improvement in the number of published papers would not change this ratio enough to affect the ratings. Increasing the NASA funding for these three missions would increase the number of publications.

Health of the Science Program: This assessment recognized the additional analysis funding available through ADAP, but also considered the added risks and inefficiencies in conducting a program through that mechanism.

2. A Category Approach

Another way of measuring the worth of a program is by asking whether it is meritorious within its mission class as well as where it falls within that mission category. This avoids the problem of comparing a tiny mission to a very large one. The missions naturally divide into familiar subgroups by the yearly costs. Missions are listed in order of rank within that class (left to right). Once again, this represents the gains during this two-year period of the extended stage rather than an evaluation of results from the prime period.

A. Flagship mission (50-100 M\$/yr): HST; Chandra;

Both of these missions continue to have the ability to make landmark scientific discoveries for many classes of astronomical objects. These are the two most important missions in this Senior Review.

B. Discovery Class (15-50 M\$/yr): Kepler; Fermi; Warm Spitzer;

Each mission is poised to make major contributions over the next two years, but with narrower breadth than the flagship missions. In the next two years each will be in a substantially different phase of its scientific life: Fermi will continue its main mission, adding deeper exposures and the detection of rare events; Kepler will finish its search for planets; Spitzer remains a valuable mid-infrared observatory. The SRC ranked Kepler the highest, with Fermi and Warm Spitzer tied, so they are listed alphabetically..

C. Explorer Class (5-15 M\$/yr): Swift;

Swift's ability to respond to a wide range of different transient events has led to a steady stream of unanticipated scientific achievements. Its range of applications continues to grow.

D. International Collaborations (1-7 M\$/yr): Planck; XMM-Newton; Suzaku :

For relatively modest contributions and at very low ongoing costs, US scientists have access to two major ESA missions in Planck (Discovery Class equivalent) and XMM-Newton (Flagship equivalent) as well as the Japanese Suzaku mission (Discovery Class equivalent). The Senior Review felt that Planck and XMM-Newton were tied, so they are listed alphabetically. It placed Suzaku slightly behind the other two, but notes that it is also much less expensive. The scientific programs of all three missions are very strong.

The conclusion from both ranking strategies is that there are no "clunkers" in the group. This is a strong suite of missions making excellent progress on a wide range of scientific issues. They are all fully deserving of NASA support.

Additional Comments

The SRC is concerned that for some missions the GOs receive inadequate funding to extract and publish the science. The SRC recommends this problem be solved by allocating sufficient GO resources directly to the missions as discussed in the individual mission sections

Relative to the prime phases, missions in the extended phase are expected to reduce costs quite significantly. Missions respond to this challenge in different ways, often with clever solutions. It may be worthwhile to have a forum to share these approaches, as it may benefit newer missions struggling with cost reduction and older missions searching for additional savings. NASA might consider convening an occasional workshop where missions describe their activities (e.g., Mission Operations) and the cost savings procedures that they have put in place or are considering. In such a workshop, NASA might invite additional outside experts and representatives from past missions that were particularly successful in cost reductions. Information presented at the meeting should be preserved and made publically accessible. There may well be design choices implemented during mission development that would allow for lower-cost extended operations after the prime phase. NASA might try to identify such approaches.

Missions:

1. The Chandra X-ray Observatory

The Chandra X-ray Observatory, NASA's flagship mission for X-ray astronomy, was launched in July 1999. Chandra's key feature, X-ray optics with sub-arcsecond angular resolution, enables a wide range of astrophysical discoveries. Its focal plane instrumentation comprises: (1) the Advanced CCD Imaging Spectrometer (ACIS), consisting of two CCD arrays, one for spectrally resolved, high resolution imaging over a 17 arc-minute field of view from 0.2-10 keV, and a second array designed for moderate and high-resolution X-ray spectroscopy when used with the High Energy Transmission Grating (HETG) or the Low Energy Transmission Grating (LETG); and (2) the High Resolution Camera (HRC), consisting of two microchannelplate arrays, one used for wide-field imaging making full use of the Chandra X-ray mirrors' angular resolution, and a second that can be used with the gratings. In addition, Chandra's highly eccentric orbit makes it ideal for long pointed observations.

The allocation of observing time takes place through the proposal process, which has been modified over time, in consultation with the Users Committee, to accommodate Large Proposals (0.3 - 1 Msec) and Visionary Projects (1 - 6 Msec), along with the smaller General Observer proposals (< 0.3 Msec). In addition, there are Archival and Theory categories for proposers. Proposals also have the opportunity to request time on HST, XMM-Newton, Suzaku, NOAO, or NRAO on the same proposal for multiwavelength programs where this is necessary. The oversubscription rate for observing time continues to be quite high (5.6). The proposer base is very broad, with over 3000 different PIs and Co-Is participating in the various Chandra programs. The production rate of papers is also high, with observational results being published within a few years of the date of observation.

a. Spacecraft/instrument health & status

The Chandra spacecraft health is excellent, with very few anomalies in over 12.5 years of operation. Slow degradation in the spacecraft's multilayer insulation has resulted in elevated temperatures on the sun-facing side, adding complexity to scheduling, but with no science impact foreseen during the remainder of this decade. A secondary impact of this effect has been the significant performance degradation of the primary radiation monitor (used to ensure safing of the scientific instruments during radiation belt passages or from solar particle storms). As a result, such functions are now performed using background information from the HRC. Chandra operates using one of two redundant gyros (each with two rotors). One of the rotors experienced a high bias current early in the mission, but this gyro has been switched over its alternate rotor, with no further issues. The mission can continue to operate using backup modes should additional gyro problems surface. The instruments continue to operate as expected. An initial CCD charge transfer inefficiency (CTI) increase caused by X-ray mirror scattered protons resulting in poorer non-dispersive spectral resolution has now been largely mitigated through a change in the CCD operating mode. The expected much slower and gradual CTI increase from the radiation belt passages is predicted to produce insignificant losses in science for 40 years. Finally, the (cold) optical blocking filters on the ACIS CCDs have developed a layer of contamination degrading the low energy response. However, this effect is being monitored and is now reasonably well understood. Level I science requirements for throughput will not be significantly affected for at least 5 years.

b. Science Strengths

Chandra has the sensitivity, angular resolution, and spectral capability to make major contributions to practically every field of astronomy and astrophysics. The observational parameter space that it accesses is deep, which is the reason that Chandra continues to make important discoveries even in the second decade after launch. The most important feature of this X-ray observatory is the sub-arcsecond imaging, which is more than an order of magnitude better than the next best instrument (XMM-Newton with 15" resolution). There is no instrument planned for at least the next two decades that will have an angular resolution approaching that of Chandra. In addition, gratings provide high-energy spectral resolution at energies above 2.5 keV, a unique capability at this time.

While there are uncertainties in identifying future accomplishments, we anticipate contributions to the understanding of dark energy through the use of galaxy clusters as cosmological probes. Galaxy clusters are excellent laboratories for studying a wide variety of phenomena, including feedback processes from AGNs, the history of abundances over cosmic time, and cluster merging processes, which can separate the gaseous baryonic and dark matter. The study of accreting black holes and neutron stars is likely to continue to be tremendously productive. Expanded surveys will measure the evolution of both obscured and unobscured black holes, providing insight into the growth, hosts, and energy production in these systems. Chandra will be able to determine more precisely the equation of state of the ultra-dense matter constituting neutron stars: this can be accomplished through high-resolution spectra in conjunction with monitoring flux data from other X-ray satellites. The range of possible breakthroughs is great, which accounts for the large oversubscription rate and the imaginative proposals that are submitted. Chandra delivers the quality of science that is expected from a flagship mission.

c. Relevance to NASA priorities

Two of the three scientific questions in NASA's Science Mission Directorate 2010 Science Plan for Astrophysics are broadly addressed by Chandra, which also contributes to the third question. The studies by Chandra of supernovae, neutron stars, along with both stellar and supermassive black holes help answer the question "How do matter, energy, space, and time behave under the extraordinarily diverse conditions of the cosmos?" The studies of the evolution of galaxy clusters, active galactic nuclei and galaxies help to answer the question "How did the Universe originate and evolve to produce the galaxies, stars, and planets we see today?" The study of stellar X-ray flares in young stars influences the evolution of planet-forming disks and the habitability of planets, contributing to answering the question "What are the characteristics of planetary systems orbiting other stars and do they harbor life?"

d. Data accessibility

Most of the data are proprietary for 12 months, after which they enter the archive and become public; some of the data have no proprietary period. Data in the archive, including reprocessed versions are accessible online with excellent web-based search and retrieval tools. Data transfer is rapid (usually a day or less). Data previews are included with the release of the data providing a useful quick-look capability.

e. Synergy with other missions and ground-based work

Many Chandra observations are combined with data from other observatories, both in space and on

the ground. The multiwavelength programs encompass a wide range of phenomena, from the Chandra Deep Fields, to the interaction between radio lobes and the hot medium in galaxy clusters. It is anticipated these synergies will continue to expand with, e.g., the release of large numbers of galaxy clusters detected through the Sunyaev-Zeldovich effect by space and ground-based programs, or NuSTAR detections of partially absorbed AGNs. During the proposal process, Chandra offers the opportunity of obtaining needed complementary observations from other observatories (e.g., HST, and visa versa). Requests for rapid response to events has been quite good through the use of Director's Discretionary Time, within the constraints of the sky available to Chandra at the time of request.

f. Proposal Weaknesses

1. While the budget for Chandra has been reduced considerably since its prime phase, the extended mission costs are still quite significant. At some point, this current cost level may become an obstacle to further continuation, leading to a loss of a powerful instrument with a unique capability. The SRC encourages the Chandra team to examine ways in which the operations costs can be reduced significantly, even if it results in a modest loss of observing efficiency. Investing in innovative ways to reduce costs now could result in a longer lifetime for the mission.

2. The funds and observing time devoted to maintaining the instrument teams now appear to exceed reasonable compensation for time devoted to maintaining the instruments and improving their operation. The Senior Review endorses the principle that, at this point in the lifetime of the Chandra mission, all observing time (except for the Director's Discretionary Time) should be competed and assigned openly through the peer review process. The SRC recognizes the desirability of maintaining the involvement of the best possible instrument expertise through the life of the mission, but agrees with the conclusion of the previous Senior Review that the existing system no longer represents an equitable or efficient solution – it needs to be reorganized and renegotiated for the extended mission.

g. Overall assessment and recommendations

Even after more than a dozen years of operation, Chandra continues to make scientific contributions at the level expected for a flagship mission. These contributions are in nearly every field of astrophysics, and the scientific impact is broad. The quality of the science has not declined significantly over time even as there are shifts to longer observing programs that are required to build statistically significant samples or to make deeper observations in fields of special interest.

The health of the spacecraft and instrument package is good and there are no obvious impediments to extending the life of the mission at its current level of performance. The optics are essentially unchanged since launch, delivering sub-arcsecond imaging near the optical axis, a level of performance that will not be approached (by an order of magnitude) for at least one and probably two decades, as the development of lightweight optics with this resolution is still at the concept stage.

During the past few years, the Chandra mission has absorbed significant cost reductions mainly in staffing with no major decline in performance or data delivered to the observer. Further savings may not be possible with the current system and its exemplary dedication to observing efficiency and data delivery. However, as available funds decline, to keep Chandra operating while maintaining the overall balance of NASA's astrophysics program it may be necessary to seek further cost reductions, even at the expense of some observing efficiency. The SRC strongly urges the Chandra team to consider all possible avenues in pursuit of savings.

An arrangement to provide observing time and financial resources to the instrument teams (GTO) was valuable and appropriate during the prime stage of the mission, but this far into the extended phase, new arrangements should be sought. The SRC recommends that the time currently allocated to the GTO teams be openly competed through the peer review process. This system needs to be reorganized and renegotiated for the extended mission.

The Senior Review recommends an extension for Chandra with the proposed in-guide budget for FY2013 and FY2014. In addition, the committee recommends the proposed augmentation to increase the GO budget. We recommend an extension through 2016, although the appropriate level of support should be examined at the next Senior Review.

2. The Fermi Gamma-ray Space Telescope

The *Fermi Gamma-ray Space Telescope* provides a unique and novel view of the high-energy universe. The Large Area Telescope (LAT) is a wide-field pair-conversion telescope covering 20 MeV to > 300 GeV, with unprecedented sensitivity, angular resolution, and sky coverage. The Gamma-Ray Burst Monitor (GBM) is an array of wide-field NaI(Tl) and BGO scintillators, covering the energy range between 8 KeV and 40 MeV. Together, these instruments survey the entire sky every ~3 hours, covering over seven decades in gamma-ray energy. All science data are released immediately to the public through the FSSC. Fermi was launched in June 2008, and commenced science operations August 4, 2008. Fermi was planned as a 10-year mission, designed for a 5-year prime phase that ends August 2013. The observatory is a partnership between NASA, the Department of Energy, and agencies in France, Germany, Italy, Japan, and Sweden.

a. Spacecraft/instrument health & status

The Fermi spacecraft and instruments were designed and tested for a 5-year mission (10-year goal), and to date have undergone no degradation that affects science performance. Neither the instrument nor the spacecraft has consumables. The LAT tracker has had 0.06% of the channels deactivated, mostly at mission start. The LAT calorimeter has had a predicted, and correctable 2% decrease in light yield due to radiation damage. Also, one readout on one crystal (out of 1536) failed, but the crystal remains operational due to a redundant readout. The GBM meets all science requirements and is operating as designed. The spacecraft subsystems are working properly. An early decrease in battery capacity was solved with a modified observing profile, which improved the thermal environment. Fermi utilizes Reaction Wheel Assemblies (RWAs) that have experienced on-orbit failures in past missions. The FOT and project engineers are monitoring them closely and developing contingency plans for safe mode operations and de-orbiting in the case of one or more failures.

b. Science Strengths

Fermi has several key capabilities that lend to its overall science strength. It has opened the previously unexplored 10-100 GeV energy range, connecting at high energies with ground-based VHE telescopes. By continuously surveying the entire sky every three hours with a baseline spanning years, Fermi is at the forefront of Time Domain Astronomy (TDA) and enables great flexibility in performing multi-wavelength observations with other telescopes. The combination of LAT and GBM

cover over seven decades in gamma-ray energy.

Fermi has more than tripled the number of known high-energy gamma-ray emitters. One of the mission's major successes has been the large number (>100) of gamma-ray pulsars discovered, which is shedding new light on both radio-quiet pulsars and millisecond pulsars. With over 1000 gamma-ray bright AGN, Fermi is providing a more unified picture of gamma-ray emission from galaxies, as well as studying long-term variability of these sources. Studies of Pulsar Wind Nebulae, SNRs and diffuse emission are providing new insights into the mechanisms of particle acceleration, diffusion, and cosmic ray production in our galaxy and nearby neighbors. Especially notable are the discoveries of the Crab Nebula flare and the "Fermi Bubbles," as well as maps of the diffuse emission in the Milky Way and nearby galaxies.

Extended operations will enable several science enhancements for Fermi. Longer integrations will extend spectral sensitivity to higher energies, constraining the extragalactic background above 600 GeV, and probing potential DM signatures over two decades in mass. Longer observations will extend study of source variability over longer (year) timescales. Overlap with ALIGO will enable GBM to provide electromagnetic confirmation for ALIGO candidate detections of GWs from coalescing binaries.

c. Relevance to NASA priorities

Two of the three scientific questions in NASA's Science Mission Directorate 2010 Science Plan for Astrophysics are being addressed by Fermi: "How do matter, energy, space, and time behave under the extraordinarily diverse conditions of the cosmos?" and "How did the Universe originate and evolve to produce the galaxies, stars, and planets we see today?" In addition, Fermi's study of solar activity and the inner heliosphere addresses the Heliophysics question "What causes the Sun to vary?"

d. Data accessibility

Both the LAT and GBM operate primarily in wide-field survey modes, with immediate (~10 hour) public release of all data through the FSSC, the external access point for Fermi data products. The FSSC also provides the Fermi analysis software and documentation. The Fermi observing mode requires a markedly different model for the GI program than most observatories, since most users do not need to apply to the GI program to request observations or data. For the LAT, the data are composed of calibrated photon event files and exposure files. In addition, the LAT data pipeline includes higher-level products such as GRB localizations, daily and weekly light curves of selected sources, and searches for slower transients. The LAT team also produces a comprehensive catalogue of sources. The GBM data is composed of improved GRB positions, light curves, spectra, and detector response matrices. The GBM team also produces a GBM catalog of all triggered GRBs.

e. Synergy with other missions and ground-based work

The NRAO, NOAO, and Suzaku observatories provide data through the *Fermi* GI program, and discussions are underway to expand this program to include VERITAS and Arecibo. The Science Support Center works with the community to coordinate these observations. Given its wide field of view, frequent all-sky coverage, and broad energy range, *Fermi* is at the forefront of Time Domain Astronomy (TDA), and complements other TDA observatories coming online such as LOFAR and SKA prototype (radio), Pan-STARRS and Skymapper (optical), eROSITA (X-ray), and HAWC (TeV); as well

as ALIGO (gravity waves) and IceCube (neutrinos).

f. Proposal Weaknesses

The proposal does not present a plan for cost reduction over time. The proposal has a modest drop in the instrument operations FTE by 2014, but not at the level expected for an extended mission. While *Fermi* is still a relatively young mission, and is participating in its first Senior Review, a vision of how to maintain the *Fermi* science performance with reduced instrument operations effort levels going forward into the extended phase would still be in order.

g. Overall assessment and recommendations

The first three years of *Fermi* have been very productive, and the committee believes we have yet to see the peak of *Fermi*'s science output. The number of GIs has been impressive and is still increasing at a healthy rate. The same is true of the publication rate. The *Fermi* science results have been outstanding, and often surprising. The team developed an innovative GI program and has a strong record of supporting this program, both by dedicating substantial resources to the program as well as through immediate public release of the science data and analysis tools. *Fermi* has excellent synergy with other observatories, and is well positioned as a leading driver in the growing area of time domain astronomy.

The SRC's primary recommendation is that the *Fermi* team develops a plan for decreasing the number of FTEs supporting instrument operations as the mission enters its extended phase. The team should be anticipating and initiating development efforts that would help in this transition to leaner instrument operations. It is crucial that this plan maintain strong support for the GI program.

The SRC recommends funding at the desired level of augmentation to provide for full operations through FY14. We recommend an extension through 2016 with a review in 2014.

3. The Hubble Space Telescope

The Hubble Space Telescope was launched 22 years ago as the flagship mission among the Great Observatories, and has not been evaluated by the SR for about 10 years. In the interim, Servicing Mission 4 (SM4) took place in 2009, providing an essentially new observatory with four operational instruments, namely COS, a unique and sensitive UV spectrograph; WFC3, a sensitive panchromatic (200 – 1700 nm) wide field camera; a refurbished ACS (Advanced Camera for Surveys) and a refurbished STIS (Space Telescope Imaging Spectrograph). Competition for these resources is intense, with an oversubscription rate approaching 10. Past scientific results have been extraordinary in both impact and scope. Publically distributed images are so well recognized that this is the best known scientific telescope ever constructed.

a. Spacecraft/instrument health & status

SM4 originally scheduled for 2004, took place in May 2009, and a completely upgraded observatory is in operation today. As predicted, the COS FUV detector sensitivity is degrading, but sensitivity is still high and plans to move the spectrum to a different part of the chip are underway in order to recover

some lost sensitivity. The ACS and the STIS were repaired. NICMOS is in safe mode, and is currently not functional. The electrical power system is nominal; the solar array drive mechanism has exceeded the life test but appears nominal. Data management systems are under control. There are some concerns with the gyros, but steps are being taken to guarantee that the pointing control system remains operating nominally. Communications and thermal performance are under control. Three fully functional FGSs are managed to preserve the life of the bearings, which have degraded. A number of new observational strategies and post-observation algorithms have been developed to enhance or retain performance and flexibility observatory-wide. A complete and well-calibrated archive has been built and maintained, with appropriate tools to access it. The goal of all the technical efforts is to increase the HST lifetime to 2016 and beyond, optimistically with a year of overlap with JWST.

Despite these new and refurbished instruments, HST remains a complex mission as revealed by the problems it has encountered over the years. If orbital decay alone were the only lifetime limitation, it would not be a factor until 2024. With redundant systems, and better use of gyros and FGSs, there is some confidence in extended life despite no further SMs. The HST team estimates the probability of no failures prior to August 2016 in subsystem components, and outlines life extension initiatives.

b. Science Strengths

HST science continues to be cutting edge. Among other achievements, Hubble has determined H_0 to 3% accuracy, and has programs to achieve 1% accuracy in this fundamental cosmological parameter. High z galaxies have been detected in the Hubble UDF; the team proposes to measure cosmic variance at high z next. Super-massive black holes have been identified in most extragalactic objects, and their mass determined. Dark matter maps have been generated using sensitive gravitational lensing in galaxy clusters: more detailed dark matter maps are projected. A baryon reservoir has been found in the warm-hot IGM, a significant contribution in the search for the missing baryons. Atmospheric measurements of exoplanets will be extended to the identification of water-rich atmospheres.

Three multi-cycle programs use 25% of Hubble observing time until the end of 2013. PHAT is an optical/UV/IR survey of M31 that will improve the foundation of stellar evolution in galaxies. CANDELS is an optical/near IR study of galaxy evolution in 250,000 galaxies at $z=1.5-8$ to assess processes leading to the starburst and AGN phases, coupled with a supernova survey. CLASH is a lensing survey of galaxy clusters spanning a large mass and redshift range to provide verification of the Λ CDM structure model. The afore-mentioned SN search in CANDELS and CLASH data is being followed up by light curves and grism spectroscopy. The Nobel prize-winning team (and others) will use these data to further constrain the time evolution of dark energy. The first SN "Primo" has been found at $z > 1.5$, and improved uncertainties in this redshift regime will improve our understanding of evolutionary effects of SN on their use as standard candles. All of these topics depend on Hubble's continued availability, often in concert with observations obtained by other missions.

Beyond 2013 the Hubble team plans new large programs: extending a complete HUDF to another region of the sky and beginning several blue deep fields to test cosmic variance in preparation for JWST. There is also an "UV urgency" campaign (90-350 nm) where this spectral regime would be emphasized for many different programs before UV capability is no longer as sensitive or no longer available. (No other UV mission is currently planned.)

New frontiers include the use of precision astrometry over time to determine and use proper motions to address several topics. HST science productivity, impact, and demand are excellent, as is expected from a flagship mission.

c. Data accessibility

The data obtained with the instrument suite are processed and delivered to the GOs rapidly. The delivered data are very well calibrated and the standard data products are often sufficient for many purposes. Additional processing of the data, to obtain the very highest quality results, is made possible with software that the mission has developed. Questions relating to the data and the software are answered rapidly and with dedication. In addition, HST has an extensive archive for which they have excellent data tools. The response to archive requests is rapid and the user can choose the products they need.

Hubble maintains calibration software for each data epoch: aging instruments need new calibrations as instrumental performance changes. Drizzle packages are available, including the new AstroDrizzle algorithm for combining the stacks of dithered images with different geometries used for CANDELS. Hubble has implemented OTFR - on the fly reprocessing of raw data with the latest calibration pipeline and reference files. Their data management system is being upgraded to retain viability with increasing use. The team finds it necessary to ramp down user support in the FY14-15 in-guide budget. Data are released after a proprietary period: UDF data will have no proprietary period.

d. Synergy with other missions and ground-based work

There are *many* examples of synergy with other missions and ground-based results. Spitzer, WISE and Herschel require HST spatial resolution to identify component multiplicity. Spitzer, Chandra and HST probe completely different wavelength regimes, and composite images of star forming regions are consequently very illuminating. GO agreements exist with some missions. The most scientifically valuable surveys have been those that combine Hubble data with those from the other great observatories as well as with ground-based radio observatories. Looking to the future, Hubble will provide important precursor observations for JWST.

e. Relevance to NASA priorities

HST science and EPO programs address the NASA 2010 Science Plan priorities: how planets and life originate, how the universe works, and what its origin and density are, as well as the 2011 Strategic Plan goals to expand scientific understanding of the universe in which we live and inspire students to pursue STEM topics through sharing NASA mission results. HST's search for the first generations of star formation, the assembly of the first galaxies, the identification of supermassive black holes in most galaxies, and the identification of dark matter and dark energy in the universe address the universe goals as does the identification of specific atmospheric properties necessary to support habitable life on nearby exoplanets. Cosmological observations leading to refined values of H_0 and w in concert with CMB observations are also critical to these goals.

f. Proposal Weaknesses

The SRC found the overguide request to provide a source catalog and enhanced data products were not well motivated in this proposal.

Because HST has the possibility of operation into the next decade, operations and science systems costs are a significant concern. The committee found the budget justification for these costs to be obscure and inadequate. According to NASA's instructions for this senior review, "Labor, major equipment, and other expenses for both the in-guide scenario and the augmented scenario must be explained in sufficient detail to determine the cost of each proposed task". There was insufficient information to evaluate whether the budget, especially concerning the large number of FTEs supported, was justified. More transparency is required, both for the labor force and activities at GSFC as well as at STScI. The SRC questions whether all efficiencies in the program have been realized. The total number of FTEs is scheduled to decrease in the coming years and if this schedule can be accelerated, significant savings could be realized.

g. Overall assessment and recommendations

HST provides excellent, cutting edge science at a total cost of about \$95M per year, of which about \$25M annually is GO funding. Continued high-impact scientific contributions over a wide range of fields are anticipated. Great care has gone into the allocation of observing time, the delivery of calibrated data products, along with software tools for use with the data sets. The HST team has been forward-looking in developing a variety of procedures that can extend the lifetime of the mission. Unfortunately, given the lack of budget detail, the SRC could not properly evaluate the need for the current and still large staff, nor could it evaluate the expressed need to reduce GO support in FY13.

To keep HST operating while maintaining the overall balance of NASA's astrophysics program it will be necessary to seek further cost reductions, even at the expense of some observing efficiency. The SRC strongly urges the HST team to consider all possible avenues, vigorously pursuing ways to accelerate cost reduction without compromising mission safety even if some science is not enabled.

The SRC applauds HST team efforts to improve lifetime probabilities for continued operation of all 4 instruments and the spacecraft. The SRC recommends that HST be reassessed by senior reviews on an ongoing basis as the mission components age.

The SRC does not recommend that the proposed budget augmentations be funded. The SRC recommends an extension through 2016 with review in 2014.

4. The Kepler Mission

Kepler is a Discovery Mission for precision photometry of stars. It is the first NASA mission dedicated primarily to the study of exoplanets, and the mission is designed to detect planets down to Earth size by their transit in front of the host star.

The mission was launched in March 2009 to an Earth-trailing orbit with communications via the deep space network. The survey mission began in April 2009, monitoring ~170,000 stars in a crowded field near the galactic plane. The scheduled mission duration was 3.5 years, based on the requirement of detecting 4 consecutive transits from each Earth-like transiting planet candidate. The mission was

intended to be extendible to 6 years or more. At the writing of the SR proposal, Kepler had detected more than 2000 candidate exoplanet systems, with from 1 to as many as 6 planets in each. Prior to the mission, there were questions in the community about the likelihood of false positives among Kepler exoplanet candidates but the Kepler team has developed excellent validation techniques based on the mission data and other available information. Follow-up has shown that an estimated 90% of the candidates are expected to be true exoplanets. An important goal of Kepler is to determine the number of potentially habitable planets, based on an analogy with the Earth and the solar system. This is often expressed as η_{\oplus} , which is variously defined, but can be thought of as the fraction of Sun-like stars that have a rocky Earth-mass planet in the habitable zone. Early results from Kepler indicate that it will not be possible to make enough detections of such planets in the 3.5 year mission to give a good value for η_{\oplus} as a result of the higher variability of typical solar-like stars compared to the Sun, upon which the mission design was based. A mission extension to 6-8 years of operation is expected to recover this original mission goal.

a. Spacecraft/instrument health & status

The spacecraft health is excellent. The detector noise is very slightly larger than the design goal, and one of the 21 CCD modules has failed. Observing efficiency (accounting for programmed interruptions) is 92.6%, predicted to decrease to 89% by FY14, with a likely significant decrease in FY15.

The team has done outstanding work in characterizing the photometer performance and in improving the pipeline to provide better photometric series in successive data releases. They have a good understanding of the noise sources in their light curves.

b. Science strengths

Kepler has great strengths in exoplanet studies in determining the frequency of occurrence of planets, their distribution by fractional size, orbit, and the architecture of exo-systems. For some of the multi-planet systems, masses can be estimated through transit timing variations that are gravitationally induced. These will become more accurate as the mission continues. For some of the brighter candidates, direct confirmation and an accurate mass will be possible through Doppler measurements. The proposal highlights spectacular results, some of which could not have been foreseen with any confidence. In particular, the statistical size distribution at small radii is an important and robust result that will benefit from observations in the extended mission. Also the multi-planet results were wholly unexpected and transformational. The sheer number of detected targets validates the Kepler approach of a very sensitive, long-duration mission. The Kepler team has shown that the number of detected Earth radius planets in the habitable zone will increase faster than linearly with time during a mission extension. It is also important to remember that the transit technique is the only way to get a direct measurement of the planetary radius. This is needed to determine the bulk density and hence vital for comparison with theoretical models. There are several other missions under study that aim to apply this technique to much brighter stars than Kepler and over a significant proportion of the sky. These surveys may produce >1000 planetary transits. However, no capability that will replace or surpass Kepler for Earth-size exoplanets is in development.

Kepler has revolutionized the study of stellar seismology and variability in general, showing that all stars are variable at low levels, detecting a wide variety of both expected and unexpected types of

variability, and showing multiple novel uses of long, precision photometric time series. Kepler time series data on main sequence stars constitutes a virtually definitive study. Remarkably, Kepler measurements of stellar oscillation modes can discriminate between the giant branch stars burning helium in the core from those, externally similar, burning hydrogen in a shell. In the future, the Kepler light curves will provide strong tests of stellar evolution theory. Kepler offers a revolutionary capability in the study of binary star systems, revealing such effects as Doppler beaming and tidally driven pulsations.

Kepler offers a new technical capability, opening a new measurement parameter space, and as often happens with such developments, this has led to unexpected results. The steadily improving pipeline is producing substantial benefits in data quality, enabling new discoveries in the data archive. There is a continuing stream of new findings - the assimilation and exploitation of new opportunities is just beginning and in some cases requires new targets and new time series for follow-up.

Kepler has a GO program, which is planned to be increased in an extended mission.

c. Data accessibility

All releases of Kepler data have occurred ahead of the dates to which the mission had committed. The release schedule has been accelerating and is now 9 months ahead of plan. Data acquired in the proposed extended mission will have no proprietary period. The mission will reprocess the entire mission data set with an improved pipeline. Currently data are archived at MAST. A second archive will be provided at the NASA Exoplanet Archive, hosted by NExSci, with value added including information from the Kepler Science Analysis System and derived science products.

d. Relevance to NASA Priorities

A NASA goal in Astrophysics is to “Discover how the universe works, explore how it began and evolved, and search for Earth-like planets.” One of the three scientific questions emanating from this goal is, “What are the characteristics of planetary systems orbiting other stars, and do they harbor life?” Kepler represents the most ambitious effort ever undertaken to obtain basic data about the make up of planetary systems around other stars and to measure the frequency of exoplanets similar to the Earth. No NASA mission concept under consideration for the next decade will exceed the completeness of Kepler for the tally of Earth-radius exoplanets. (WFIRST is expected to reach similar total detections of Earth-mass planets in the habitable zone, though for much more distant stars. WFIRST has advantages over Kepler including detection of very low mass, large orbit and free-floating planets.)

The 2010 Planetary Astronomy decadal survey stated that it is vital to determine “key issues such as planet frequency” within the next decade. The New Worlds, New Horizons survey committee recommended “exploitation of the current Kepler mission.”

e. Synergy with other missions and ground-based work

While Kepler produces its own follow-up for some targets, most require other resources for confirmation or follow-up, usually some combination of imagery and/or spectroscopy. For some candidates, transits can be observed at other wavelengths, usually from space, primarily by Spitzer, sometimes providing information about the presence and composition of an atmosphere. The Kepler

extended mission proposal includes a coordinated program supported by the mission for limited follow-up of small planet candidates. Currently, Kepler follow-up observations make the largest use of NASA/Keck observing time, obtaining deep imaging to detect other stars within the photometer aperture and to measure or set a limit to the Doppler motion of the target.

f. Proposal Weaknesses

Since masses cannot be determined, Kepler can only directly measure an upper limit to η_{\oplus} . The proposal over-emphasizes the capability of Kepler to directly determine η_{\oplus} as compared to the contribution of Kepler determination of exoplanet statistics. The strong focus of the proposal on the detection of a few (e.g. 0 – 20) “Earth-like” bodies leaves the plan subject to criticism for the very high dollar cost of a few new objects, few or none of which can be followed up for mass characterization through Doppler shift measurements.

In the discussion of the extended mission, the proposal does not fully address the selection of new stellar physics targets within the field or the added value of longer time series for current targets (except in the case of magnetic cycles). Similarly, the results reported thus far only partially represent the productivity of the fully reprocessed prime mission, and the committee could not clearly distinguish the eventual production of the prime mission from the added value of the extended mission.

g. Overall Assessment and recommendations

The Kepler mission is an outstanding success. Kepler is not only a unique source of exoplanet discoveries, but also an organizing and rallying point for exoplanet research. It has enabled remarkable stellar science. It is somewhat difficult to evaluate the need for the extended mission, as results published to date cover only part of the reprocessed prime mission. Based largely on demonstrated achievements and the steady flow of new results, the SRC gives high priority to continuing Kepler into an extended mission. The SRC endorses the Kepler plan to continue and expand the GO program, and is keen to see the end of the proprietary period and prompt release of the level 1 data products (light curves) in line with the timeline in the proposal. The SRC supports the requested augmentation for additional science opportunities, which extends GO support to important aspects of exoplanet science as well as other areas.

A large fraction of the cost is for science operations, and the mission should consider carefully how they can reduce these and other costs in the extended phase. In the event of insufficient resources, NASA should consider all possible economies. If the full extended mission is not funded for any reason, NASA may wish to consider extending the data analysis and follow-up programs, as these are providing high value-added for the community. The SRC recommends an extension through 2016 with a review in 2014 to consider particularly the incremental value of further extension to the determination of η_{\oplus} .

5. The Planck Mission

Planck is an ESA-led cosmic microwave background (CMB) mission designed to map the temperature and polarization anisotropies over the full sky. Planck has two instruments sharing the focal plane: the Low Frequency Instrument (LFI) consisting of actively cooled (20K) high electron-mobility transistor (HEMT) amplifier based detectors in bands at 30, 44 and 71 GHz, and the High Frequency Instrument (HFI) consisting of 0.1K bolometers in six bands from 100 to 857 GHz. Science observations began in August 2009.

Planck is the next generation all-sky CMB mission after WMAP using higher resolution (3x) to measure higher multipoles, and using nine frequency bands to separate and characterize astronomical foregrounds to the CMB, which are also of astrophysical interest.

a. Spacecraft/instrument health & status

The spacecraft has been remarkably robust. As expected, the supply of He3 required to cool the HFI 0.1K bolometric detectors was exhausted after 29 months of operation. The 20K cooler will likely need regeneration if the extended 12 month LFI is pursued. This is not expected to be a problem. Planck recently completed an approved 15.5-month baseline extension using both the LFI and HFI instruments.

b. Science Strengths

COSMOLOGY: Planck's primary science is to make precise measurement of the cosmological parameters that govern the evolution of our universe, and in particular to explore and constrain extensions to the standard 6-parameter cosmological model. These advances are enabled by making cosmic variance limited measurements of the CMB angular power spectrum up to multipoles of 2000 in temperature, and by making dramatically improved, although still statistical noise dominated, measurements of the polarization power spectrum. The temperature data will provide much higher precision of the standard 6-parameter cosmological model (3x to 5x compared to WMAP). More importantly, Planck's extended reach to higher multipoles which includes coverage of the exponential damping of the primary CMB anisotropy at high multipoles, will allow constraints on extensions to the cosmological model, such as non-zero curvature, the equation of state of dark energy, the number of relativistic species, the masses of the neutrinos, the helium abundance, and running of the scalar spectral index. The data will also be used to constrain the statistical nature of the initial fluctuations, another probe of inflation. The polarization data will provide independent tests of the cosmological model and additional precision of the parameter constraints. On large angular scales, the Planck polarization measurements will probe the reionization of the universe and provide competitive constraints on the level of B-mode polarization from inflationary gravitational waves.

ASTROPHYSICS: Planck's all-sky maps in nine frequency bands are sensitive to astrophysical sources of great interest to the broader community, including galaxy clusters via the Sunyaev-Zel'dovich (S-Z) effect, dusty galaxies, radio galaxies, and the interstellar medium of the Milky Way. They will have enormous legacy value. The initial catalogs released in January 2011 are already having a large impact. For example, they are already being used to characterize the cosmic infrared background (CIB) and the population of massive galaxy clusters in the local universe. The polarization data will be particularly valuable for studies of the Galactic interstellar medium.

c. Relevance to NASA priorities

Planck measurements and analysis of the CMB addresses the NASA strategic goals, “What are the origin, evolution, and fate of the Universe?” and “How do planets, stars, galaxies and cosmic structure come into being?” The nine band all-sky maps and the extracted foreground maps will also provide additional important information on the evolution of the universe, the structure of the Galaxy and the process of star formation.

d. Data accessibility

The first Planck results were published on schedule with a set of 26 articles in a dedicated volume of A&A (V536) in December 2011. These are non-cosmology, non-polarization results from the first year of observations. They include all-sky source catalogs and a new all-sky catalog of massive S-Z-selected galaxy clusters.

The first cosmology results and data products are currently scheduled for release in early 2013, including the public release of sky maps and component maps, power spectra and the likelihood function, source catalogues, and scientific results based on 15.5 months of data (the baseline mission). This first cosmology release will include temperature and polarization data for LFI, but only temperature data for HFI. Time ordered (i.e., raw) data will not be included in this release.

The second release of cosmology results and data products is scheduled for early 2014. This release will be based on the full mission data (29 months HFI, projected 42 months LFI), including polarization data for both instruments. Time ordered data will be included in this release. At this point all data would be publicly available.

A third and final release of cosmology results and data products has been proposed and would be projected for early 2015, based on a second and improved analysis of the full 29-month HFI and 42-month LFI data.

e. Synergy with other missions and ground-based work

Observations for the prime science mission of Planck, i.e., precision CMB anisotropy measurements, are self-contained within the mission. The cosmological results will, however, inform many other science investigations, and Planck’s precise calibration of the CMB power spectrum will be used to calibrate all future CMB experiments. The all-sky maps, foreground maps and source catalogs have high synergy with other missions and ground-based work, e.g.: Chandra, XMM and Suzaku for follow-up of Planck S-Z galaxy clusters, optical/infrared galaxy clusters surveys, Herschel and ground based mm and submm surveys to characterize the cosmic infrared background, and many others.

f. Proposal Weaknesses

The proposal contained insufficient quantitative information for the SRC to understand fully the improvement in the systematics of the beam response and calibration that would be enabled by the 12-month extension of the LFI. This is likely due in part to not yet understanding all of the data reduction issues at this early stage in the analysis.

The proposal did not sufficiently discuss the synergies of the Planck CMB mission with the ongoing sub-orbital and ground-based CMB projects.

Insufficient information was given to understand the budget fully.

g. Overall assessment and recommendations

Planck is an exciting experiment probing the fundamental workings of the universe. It is proceeding extremely well. The community eagerly awaits the cosmology results and access to the CMB and foreground data. The CMB maps, the foreground maps, and the nine frequency band maps will have enormous legacy value. Assuming the calibration and systematics are well controlled, Planck will produce the definitive measurements of the primary CMB temperature anisotropies. The US is also playing a critical and highly visible role in this ESA-led project.

The in-guide budget appears appropriate to carry out the work covered. The proposal also requests a budget augmentation for the following: Support for the additional year of operation of the LFI already approved by ESA; support for an additional year of analysis of the full Planck dataset, HFI+LFI, leading to a third and final data and science release in early 2015; and support for an additional year of operation of the US Planck Data Center and Data Archive, leading to the 2015 release.

The LFI extension is motivated primarily to improve the knowledge of the beam response, improvement of the calibration, additional jack-knife tests of the noise model, as well as improved sensitivity of the LFI bands. The cost is primarily to support instrument operations, with a single FTE. These type of measurements and tests of systematics are critical to the CMB analysis. The expected improvements in the calibration and the resulting improvement in the cosmological constraints were not provided to the SRC, and probably are unknown at this time. Given that ESA has approved the extension and that the calibration and systematics will be the ultimate limit of the Planck results, the SRC recommends proceeding with the 12 month LFI extension. Further extensions, hinted at during the team presentation, would have diminishing returns, requiring better and more quantitative justification to be considered.

CMB analysis is complicated in general, and the analysis of the Planck data will be exceptionally difficult given its all-sky coverage, nine frequency channels, polarization data, and two detector technologies. Therefore in this augmentation it is requested to keep the analysis team intact, as well as the US Planck Data Center and computing support, to conduct a third and final cosmology data and science release in 2015. The SRC is sympathetic and notes that WMAP was extended for similar purposes. The third data release has also been proposed to the European partners and a decision is expected by the end of the current year. The SRC recommends an extension through the planned second cosmology data release (early 2014) and that NASA follow the European partner's decision in whether or not to support the third data release, and if successful, work with the US Planck team to determine the appropriate support level and subsequent project phase out.

6. The Suzaku Spacecraft Mission

Suzaku is a joint Japanese-U.S. X-ray astronomy mission, launched by the Japanese Aerospace Exploration Agency (JAXA) in July 2005. Developed in a close collaboration between the Institute for Space and Astronautical Science (ISAS/JAXA) and U.S. instrument teams, it combined a number of large-area X-ray telescope modules with a microcalorimeter supplied by NASA/GSFC (the XRS) and a CCD-based imaging spectrometer (XIS: 0.2-12 keV, 19' square FOV, about 2 arc-min spatial resolution, spectral resolution 140eV FWHM at 6 keV), as well as a separately collimated hard X-ray detector (HXD: 10-600 keV, 34' square FOV, 0.5-4.5 degree angular resolution, about 4keV at 20keV spectral resolution). After the unfortunate failure of the XRS He dewar system early in the mission, the remaining primary instruments still provide a unique combination of features, including the broadest energy range of large-area X-ray missions, superior CCD-based spectral resolution at low energies compared to other X-ray missions, high effective area (comparable to or greater than Chandra at 1 -12 keV), and very low internal background. The instruments are by now well-understood and particularly well-calibrated. Suzaku is therefore a powerful scientific tool, applicable to wide variety of X-ray astronomy investigations, and especially suited to studies of low surface brightness objects such as galaxy clusters. Evidence of this fact is the continuing demand for new Suzaku observations, which is currently oversubscribed by a factor of about 4. The US (or US-led collaborations with Japanese) investigators receive about 50% of the available observing time.

a. Spacecraft/Instrument Health & Status

The current health of the spacecraft is very good, with no major issues. The Japanese space science steering committee has made a strong recommendation to operate Suzaku at least until July 2015 so that it can overlap with ASTRO-H observations. The predicted orbital lifetime is greater than 10 years. Of the 4 CCDs comprising the XIS, one failed due to a micrometeoroid impact (thus reducing the effective area, since each CCD has a separate telescope module). Minor issues in 2 others do not significantly compromise science. Contamination on the cold optical blocking filters (reducing low-energy X-ray throughput) has increased over time, but appears to be slowing, resulting in an additional throughput loss at 0.6 keV of no more than 25% over the next two years. The HXD detector is operating nominally, with response changes < 5% below 70 keV, and < 10% below 300 keV.

b. Science Strengths

As indicated above, the Suzaku instrument complement makes it in many ways uniquely suited for a wide variety of important astrophysical studies. For example, Suzaku's exceptionally low background allows mapping of the X-ray temperature and density profiles at and beyond the virial radius of galaxy clusters. This study is being carried out as a (competitively awarded) Suzaku "Key Project", leading to a better understanding of physical processes in the intra-cluster medium and thus helping to solve outstanding cluster formation problems. In addition, Suzaku's CCD imaging spectroscopy capabilities are well suited to studies of supermassive black hole spins and the physics of relativistic jets in AGN that address some of the fundamental questions in AGN physics. Simultaneous or near simultaneous observations of these objects with the microcalorimeter on ASTRO-H (much higher spectral resolution but lower effective area) have the potential to yield much better constraints on physical models than with either Suzaku or ASTRO-H alone. Spectral mapping of the Cygnus Loop with Suzaku has revealed low-energy spectra that require additional lines not included in the usual SNR diffuse gas models, providing strong evidence for charge exchange reactions in the outer rim of the Loop. Suzaku

science (all proposed by GOs) encompasses a wide variety of other topics such as studies of stellar mass black holes, neutron stars, and white dwarfs, to name but a few. There are no signs of interest abating from the scientific community as evidenced by a continuing rise in Suzaku publications over the past several years (at a rate of about 90 papers/year).

c. Relevance to NASA Priorities

Suzaku science addresses the NASA 2010 Science Plan strategic goals to discover how the universe works, as well as questions posed in the 2010 NRC Astrophysics Decadal Survey including how cosmic structures form and evolve, how black holes grow, radiate, and influence their surroundings, and what controls the mass-energy-chemical cycles within galaxies.

d. Data Accessibility

All new US and US/Japan observations are selected through peer review, and after being processed by JAXA and the GSFC pipeline, data are stored at the GSFC HEASARC with a proprietary period of one year, after which the data are made public. Data analysis tools are provided through the HEASARC with standard HEASoft software (e.g., FTOOLS, XSPEC, etc. with specific packages for Suzaku). Until recently, adequate GO support was also provided at the US Suzaku Data Center. However, significant NASA cutbacks, despite the recommendations of *augmented* funding in the 2010 Senior Review, have resulted in the data center being staffed at a level allowing only the most critical tasks to be performed (about 1 FTE scientist + 1 FTE programmer). In addition, funding was removed for support of GOs, requiring additional separate proposals to the ADAP for analysis funding.

e. Synergy with other missions and ground-based work

Suzaku has proven to have strong synergies with currently operating X-ray and gamma-ray observatories, and this will undoubtedly continue with future space observatories. For example, the Suzaku AGN Spin Survey “Key Project” is being carried out using an unbiased sample of AGN detected in the Swift survey. Suzaku is the observatory of choice for detailed follow-up of steady and flaring sources detected with the Swift BAT. Diffuse emission in star-forming regions has been studied using the excellent surface brightness sensitivity of Suzaku coupled with the high angular resolution of Chandra and XMM-Newton. The HXD on Suzaku overlaps over a wide energy range with the hard X-ray NuStar mission (launch this year), and ASTRO-H’s high-energy instruments.

f. Proposal Weaknesses

From a scientific and technical standpoint, this proposal has essentially no weaknesses.

g. Overall assessment and recommendations

With a powerful X-ray instrument complement, Suzaku continues to produce excellent science, ranging from studies of galaxy cluster physics to the properties of supermassive black hole accretion disks and jets. This is evidenced by a growing number of publications and a significant oversubscription rate in observing time for its GO program, in which the US can access up to 50% of all observing time. In large part because of a strong Japanese-U.S. collaboration in hardware, data processing, and science, the US Suzaku data center and GO program maintain a high level of scientific productivity despite an insufficient budget.

Although SRC 2010 strongly recommended an augmentation to Suzaku's data center and GO support budgets, subsequent budgetary pressures forced NASA to subsume the Suzaku GO program in the ADAP. This required GOs to re-compete for scarce financial support in order to analyze the data from observations that they had been previously awarded. In addition, the maintenance of the Suzaku data center and science team support was reduced to an inadequate level. Given the scientific impact of Suzaku and its importance to the long-standing U.S.-Japanese collaboration in space science and implications for future collaborations, the SRC strongly believes that this situation is not sustainable.

Consequently, the SRC recommends an extension through 2016 with review in 2014, and we have two specific recommendations:

- 1) The Suzaku data center support should be increased *beyond* the augmentation requested by the mission, to \$0.7M annually.
- 2) The GO program should be given sufficient yearly funding to adequately support successful proposers with highly rated new observations. The SRC estimates this level at \$1M/year.

7. The Swift Gamma-ray Burst Mission

Swift is a MIDEX mission launched in 2004. It was intended primarily for the discovery and follow-up study of gamma-ray bursts, and consists of three instruments. The first (BAT) is a large-area, 1.4 sr field of view coded mask telescope with CdZnTe detectors covering the energy range 15 - 150 keV with ~2' angular resolution. The second (XRT) is a grazing incidence imaging X-ray telescope with CCD detectors. It is sensitive in the 0.2-10 keV range and can locate sources to ~2". The third (UVOT) is the UV-Optical telescope that covers 160-800 nm with several filters and grism spectroscopy. The spacecraft can automatically slew to a source that triggers the BAT and begin observations with the other two telescopes in less than 90 seconds. Accurate positions from the XRT are autonomously relayed to the ground network for distribution shortly thereafter.

Swift has been in extended mission phase since 2007 and currently operates with a budget of \$4.3M/year, about half of its early years budget. This does not include foreign contributions of ground station coverage and some personnel worth about \$3.5M, none of which is considered particularly at risk at this time. The baseline mission plan is to cease operation at the end of FY14. The augmented request is to add \$400K/year to the current \$800K/year GO program, and \$128 K/year for a fourth operations team member to cover absences of one of the current three. This would bring the total to \$4.9M for FY13. The mission team requests this plus an addition to compensate for inflation through FY16. (There is an error in the proposal that drops the augmentation for FY15-16.) Since the last senior review, the team has reduced the mission's costs about a factor of two. By improving automation and procedures, the operations coverage was reduced from 24/7 to 8/5 (40 hours/week) while increasing responsiveness, observing flexibility, and efficiency.

a. Spacecraft/Instrument Health & Status

All instruments and systems are operating normally and there are no issues with expendables that would limit the lifetime. The orbit lifetime is beyond 2025. The power supply for the XRT CCD cooler

failed at the beginning of the mission and numerous pixels in the BAT detector become noisy at times. Both issues are adequately handled by automated operating procedures.

b. Science Strengths

Swift has been very successful, discovering 643 GRBs and providing accurate coordinates for follow-up observations that have resulted in redshift measurements for many of these. Coupled with the ground-based follow-up it enabled, Swift has apparently solved the long-standing mystery of the nature of the long GRBs as highly energetic and anisotropic supernova explosions. Redshifts have confirmed distances to $z=8.2$, and modeling indicates that Swift is detecting GRBs at $z > 9$. Rapidly improving follow-up infrared spectroscopy should allow redshifts to be obtained for many of these, and an improved trigger scheme for the highly time-dilated events should increase the number of candidates. The GRB afterglows are very bright and can serve as backlights for measurement of metal abundances in the early universe.

The origin of the short GRBs is less certain. Source location and host galaxy identification strongly suggest that they arise from neutron star-neutron star or neutron star-black hole mergers. These events are also considered the most likely sources to be found by the Advanced LIGO instrument. Using triggers from Swift and Fermi will greatly increase LIGO sensitivity, and coincidences would confirm the association. Only Swift can provide the accurate positions required for redshift determination, which unlocks analysis of the physics of the gravitational wave detections.

LOFAR, EVLA, and ALMA are new facilities coming on line that can work in conjunction with Swift to study the physics of the spectacular supernova explosions and their GRB jets that cause the long GRB events. The first Tidal Disruption Event from a star being swallowed by a black hole has been observed, and improved triggering capabilities will hopefully allow the study of many of these.

Swift has made the most sensitive existing hard X-ray survey of the entire sky, and continues to monitor it for interesting transient events. It can autonomously get soft X-ray and UV data on these, and accurate positions for other follow-up. Studies of local supernovae with UVOT provide essential calibration for cosmological studies of distant ones, where the observable visible and near IR originate in this band. A Galactic Plane survey will locate accreting stellar mass black holes and other X-ray binaries with far higher sensitivity than existing surveys. The UVOT grism allows measurements of abundances of various gases surrounding comets, and the XRT can track charge exchange interactions between these and the solar wind.

c. Relevance to NASA priorities

Swift directly addresses all three goals in the 2010 Science Plan of the SMD. Studies of the early afterglow of GRBs explore the nature of matter and energy in the collapse process that forms a black hole. The high- z GRBs are unique probes of the re-ionization of the Universe, providing information on the effects of the first stars, and may themselves represent the final stages of these stars. Swift is also an ideal observatory for the study of gas and dust in comets, which are the most pristine local material available for understanding the formation of our own Solar System.

d. Data accessibility

All data are immediately public and easily downloadable with standard software tools available. As

many as 15000 downloads/year are registered.

e. Synergy with other missions and ground-based work

Synergy is a very strong point of the continued mission. Swift's ability to reduce error boxes from $\sim 1^\circ$ to ~ 1 arcsec with a very rapid response time, enables source identification or follow-up with yet another instrument. In other cases, it is the ability to obtain contemporaneous spectral energy distribution measurements rapidly and over a wide spectral range that complements coverage from the discovery instrument. Here we list several examples of the strong synergies of SWIFT with other projects:

Fermi: Fermi has high sensitivity for detecting GRBs, but cannot obtain good enough positions for follow-up. However, it gets sufficiently good positions with LAT that the Swift XRT can locate afterglows for 90% of them and trigger further ground-based follow-up. Swift can respond rapidly to gamma-ray flaring sources discovered by Fermi, extending spectral energy distribution coverage through hard and soft X-rays to the ultraviolet, and providing accurate positions for unidentified sources to allow ground-based coverage to longer wavelengths. Swift currently devotes about 7% of its time to joint Fermi observations.

Chandra & Hubble: Swift makes coordinated follow-up observations of short gamma ray bursts.

IceCube: Swift follows up IceCube candidate neutrino events -- expected to be nearby SNe or GRBs.

MAXI: Swift allows joint studies of black hole transients and tidal disruption events. It extends MAXI coverage to higher energies and provides improved positions. Twelve events have been registered in the past 6 months.

NuStar: The XRT has a similar field of view, angular resolution, and logarithmic flux sensitivity as NuStar. Short coordinated observations of all NuStar fields are planned to increase the range of spectral energy distribution measurements and to help identify sources discovered in NuStar deep surveys. Magnetars are important NuStar targets, and Swift will continue to discover new ones at about 1/year.

ALIGO: The most probable source class for detection by Advanced LIGO is merging neutron star systems, currently thought to be the source of the short GRBs. Fermi is more sensitive for detecting these bursts due to its larger field of view and the hard spectrum, but obtaining distances will rely on Swift positions for ground-based follow-up.

f. Proposal Weaknesses

No significant weaknesses were identified.

g. Overall assessment and recommendations

Swift has been very agile in responding to new scientific opportunities. Its unique capabilities have enabled crucial contributions to other missions and unexpected areas of astrophysics that now occupy much of their observing time. The team has responded admirably as the mission has evolved, maintaining the priority, quality, and quantity of observations for the primary GRB mission even as it

has become a reduced part of the observing program.

The proposal presents a very good possibility for exciting new science.

The SRC recommends continued funding at the requested augmented level and additional increases to GI support. We recommend an extension through 2016 with review in 2014.

8. The Warm Spitzer Space Telescope Mission

Spitzer Space Telescope is one of NASA's Great Observatories. Launched in 2003, its warm operations began in 2009 after its cryogenic mission ended as expected. In its extended "warm mission" it has two cameras operating at 3.6 and 4.5 microns each with 256x256 pixels over a 5x5 arcmin field of view, and a 0.85m mirror. It is the only telescope operating from space at these wavelengths. The telescope's performance is background limited. Science operations are provided by the Spitzer Science Center, and flight and mission operations are handled by Lockheed Martin and JPL.

The mission is currently funded for operations through FY2012 with closeout in FY2013. Augmented funding is sought for full operations in FY2013 and FY2014 with closeout in FY2015.

a. Spacecraft and Instrument Health & Status

Spitzer is in an Earth-trailing orbit gradually increasing its distance from the Earth. It is currently about 1 AU from the Earth. All spacecraft components are fully operational and redundant. The IRAC 3.6 and 4.5-micron arrays, each with about 20% bandwidth, have exhibited extraordinary stability and have a sensitivity and image quality virtually unchanged from the cryogenic mission values. Although it was originally thought that the Telescope would have to cease operations in 2013, with changes to its data compression algorithm and operations model the telecommunications system can be maintained with a single 70m DSN antenna through 2017. The Telescope has adequate power and reaction control gas, and there is no technical reason that it could not operate until 2017. The safe mode recovery procedure will be modified in 2013 to support operations well beyond 2017.

There have been significant improvements to the performance of Spitzer in recent years. Pointing stability has been improved and errors are now $<0.1''$. Precise mapping of the intrapixel sensitivity identifies a "sweet spot" where the most precise photometry can be conducted, and there are plans to reduce significantly the long-term pointing drift. The result is that photometry with errors of 30-50 ppm are now possible.

Operations are very efficient, and about 7600 hours are spent on astronomy each year.

b. Science Strengths

The telescope is doing astronomy for about 85% of all hours and is producing excellent results. As a platform for high-quality long-duration photometry in the mid-IR, it is unrivaled. Observing programs can be scheduled for many tens of consecutive hours. This capability has produced spectacular results in studies of exoplanets. Spitzer is in a unique position to exploit recent discoveries of

exoplanets by Kepler as well as other facilities, and to follow up on discoveries recently made with the WISE mission.

IRAC observations of planetary transits have the sensitivity to confirm Kepler candidates as well as characterize their atmospheric properties and, in some cases, discern the thermal and chemical structure of their atmosphere as well. Without a doubt this science is unique, compelling, and extraordinarily timely. While JWST will be capable of carrying out transit photometry, Spitzer is filling a critical role by investing thousands of hours in exploratory IR transit studies, which would be virtually impossible with limited JWST access.

The sensitive mid-IR photometry is also a boon in characterizing the SED of galaxies at $z > 7$, providing valuable data to complement that from HST and Herschel. The precise photometry makes it possible to improve the Period-Luminosity relationship of Cepheid variables, with a consequent shrinking of the uncertainty in the Hubble constant in the near future.

All scientific programs are now peer reviewed, and Guest Observers are funded at a level of \$5M per proposal cycle. The instrument is in considerable demand, with a proposal oversubscription factor of 3.8. The Spitzer Science Center is initiating a program of key projects to improve prospects for using the telescope for large significant programs with commensurate GO funding.

c. Relevance to NASA priorities

Warm Spitzer is relevant to NASA's strategic goals to understand how the Universe evolves, how planets, stars, galaxies and cosmic structure come into being, and the existence of life elsewhere. The studies of extrasolar planets bear directly on research objectives to create a census of extrasolar planets and measure their properties. The high-redshift and Cepheid studies relate to the objective to understand how the first stars and galaxies formed and evolved over time.

d. Data Accessibility

Spitzer data reside in at the NASA/IPAC Infrared Science Archive. For the General Observer and snapshot programs the proprietary period is 12 months; it may be less for other programs.

e. Synergy with other missions and ground-based work

In addition to the strong link to Kepler through target confirmation, Spitzer provides a unique follow-up capability for the characterization of bright exoplanet systems discovered in ground-based surveys. Spitzer provides complementary measurements for Planck (SZ clusters), Herschel (source identification), Wise (brown dwarf candidates), and HST (Lyman-break redshift estimates). Spitzer's success and lessons learned in reducing systematics in photometric noise continue to carry over to HST, JWST and other missions. Spitzer paves the way for efficient JWST source selection and observing programs.

f. Proposal Weaknesses

Spitzer remains an expensive mission despite efforts that led to operations cost reductions.

g. Overall Assessment and recommendations

The 2010 Senior Review recommended that even though the Warm Spitzer mission operates with about 1/3 of the personnel needed for the cryogenic mission, further economies would be in the project's interest. The SR2010 committee also considered it critical that Spitzer respond quickly to Kepler data releases, but noted that with the limited life of Spitzer (at that time the mission was estimated to end by December 2013) it would be difficult to make follow-up observations on some Kepler exoplanets until JWST is operational.

In response, the Spitzer team engineered lifetime extensions to the spacecraft so that in principle it can operate until 2017, and possibly beyond. They have also made available 1400 hours of telescope time to members of the Kepler team for confirmation and study of Kepler exoplanet discoveries. More than 5500 hours have been allocated for exoplanet observations to date.

The Spitzer team is to be commended for their work not only in transforming the telescope from a cryogenic mission to a warm mission, but also in the improvements that have made it such a powerful instrument for science, especially in exoplanet studies.

As Spitzer approaches its end of mission, further reductions in efficiency and increases in risk are acceptable.

The SRC recommends funding at the desired level of augmentation to provide for full operations through FY14, including a healthy GO funding level. We recommend an extension of the mission through 2016 with a review in 2014.

9. The XMM-Newton Mission

The X-ray Multi-Mirror Mission (XMM) was launched as a part of the ESA Horizon 2000 program in December of 1999 and remains fully operational. It has 5 X-ray instruments, 3 X-ray CCD arrays (MOS-1, MOS-2, and PN) and 2 grating spectrographs (RGS-1, RGS-2) that are co-aligned and operate simultaneously. It covers the 0.2-12.0 keV energy band (together with an optical / UV telescope) at moderate spatial resolution of 6" FWHM (15" Half Power Diameter) in the center of the 30' field of view. The reflection grating spectrometers offer R~200-800 of point sources and peaked extended sources. It supports a broad Guest Observer program with annual peer reviews of proposals. On average 180 proposals are selected from approximately 500 submissions. Over the last 5-13 years, XMM has been scientifically productive, with typically 300 papers per year, a rate that is not that dissimilar from maximum rates from Spitzer and Chandra achieved 5 years post-launch, and only about 50% fewer than Hubble. XMM time is oversubscribed (3:1) with US PIs winning around 40% of the A/B targets. (Targets are prioritized A, B, and C. A/B targets are guaranteed time, while C targets are used as filler for scheduling.)

a. Spacecraft and Instrument Health & Status

The spacecraft is working well. All XMM instruments are working at full redundancy. There is some degradation in instrument sensitivity. That degradation is being monitored and as the calibration changes, new calibrations are being provided. The anticipated lifetime of XMM extends to 2018 and possibly beyond.

b. Science Strengths

XMM is the largest X-ray telescope ever deployed. XMM provides high-throughput X-ray spectral imaging, approximately 3 times the collecting area of Chandra's CCDs. Its optics provide an angular resolution that is significantly better than that of Suzaku's, but about five times worse than that of Chandra. For spectroscopy, the RGS has the greatest collecting area of any X-ray mission in the soft X-ray band, with an upper energy cutoff at 2.5 keV. Because of its orbit, XMM can monitor targets for long uninterrupted periods. Its large field of view is suitable for studying extended sources requiring a large field or mosaics, such as the populations of Local Group galaxies, clusters of galaxies, and supernovae.

The addition of the Large Proposal and the Very Large Proposal categories to the types of proposals submitted for review creates a new scientific opportunity for the community. X-ray astronomers now can consider proposing to conduct surveys with large, statistically interesting samples of objects or sufficiently deep spectroscopic observations of individual objects. X-ray astronomy is largely still in the statistics-dominated regime, where S/N improves proportionally to the square root of exposure time.

XMM provides data with a broad scientific impact, from solar system plasma physics to cosmology. It has been productive and its results have been extremely influential. Its science highlights include the resolution of the so-called "cooling flow problem" in clusters of galaxies, a problem fundamental to sorting out how hot baryons manage to form galaxies (and stars) in deep dark matter potentials. XMM was the first to detect X-ray emission from brown dwarfs and it discovered new kinds of novae and supernovae. It discovered relativistically broadened iron lines in the spectra of neutron stars and the first quasi-periodic oscillation (QPO) in an AGN. Most recently, XMM observations reveal a time lag of 2000 seconds between the variability of the Fe K line and the continuum in the Seyfert galaxy NGC 4151. An Ultra-Luminous X-ray source, a possible harbinger of an extremely massive black hole, was recently reported in M31 (J004253.1+411422). Recently accepted large programs include a survey of stellar activity in Kepler stars, mosaics of local group galaxies and cosmological studies of Planck-selected massive clusters of galaxies. Such clusters provide powerful and independent assessments of dark matter, dark energy, and its equation of state. Because many of these tests are based on how the growth of structure occurs, any significant differences between these assessments and those of geometrical tests like supernovae and baryon acoustics oscillations are critical to testing the underlying assumptions of General Relativity.

c. Relevance to NASA priorities

The science goals and achievements of XMM are directly responsive to the 2011 NASA Strategic Plan Strategic Goal 2: "Expand scientific understanding of the Earth and the universe in which we live," and through the mission's E/PO effort Strategic Goal 6: "Share NASA with the public, educators, and students to provide opportunities to participate in our Mission, foster innovation, and contribute to a strong national economy." In addition, the XMM program is responsive to the Science Mission Directorate (SMD) 2010 Science Plan providing important advances primarily towards the Astrophysics goal to "Discover how the universe works, explore how the universe began and developed into its present form, and search for Earth-like planets."

d. Data accessibility

The XMM data center, together with the US GOF, has significantly improved the support for XMM data analysis, although the analysis of extended sources requiring careful treatments of the background remain extremely difficult. Standard reprocessing and the addition of basic image and spectral production scripts make basic XMM analysis more accessible to a broader audience, although some work remains to make XMM data as straightforward to analyze as that from Chandra.

e. Synergy with other missions and ground-based work

XMM science has much synergy with current (and future) NASA and ESA missions. For example, XMM has provided timely observations of clusters detected in the Planck data. The most recent XMM panel enthusiastically approved large programs to obtain simultaneous observations of AGN and black holes together with the to-be-launched NuStar (launch after March 2012). The Suzaku low-surface brightness studies of nearby clusters of galaxies, probing the distribution of baryons near the outermost boundaries of the virialized regions of clusters of galaxies leverage the constraints on point source contamination that can be obtained by much shorter (but higher spatial resolution) observations by XMM and Chandra. Understanding the spatial features in clusters and galaxies such as shocks and cool fronts can be enhanced by spectroscopic studies enabled by the higher throughput of XMM's instruments.

Furthermore, while much of X-ray astronomy might yet be "photon-noise limited science", there are still scientific gains to be realized by improving our understanding of the systematics of X-ray telescopes and detectors. With XMM, Chandra, and Suzaku, X-ray astronomers have a golden opportunity to confirm ground-breaking results from independent telescopes and to perform simultaneous observations of X-ray spectrophotometric flux standards.

f. Proposal Weaknesses

The proposal describes a minimal user support facility with limited support for funding GO science. There were no major weaknesses.

g. Overall assessment and recommendations

XMM is a highly capable mission in the class of the Great Observatories, offering science opportunities to the US community at low cost. The highly competitive proposal process ensures that the observatory continues to do excellent science.

The SRC recommends an extension through 2016 with review in 2014, and that NASA continue funding the US GOF at their proposed levels, but increase the GO funding support to 3 million USD per year.

Acronyms

A

A&A	Astronomy and Astrophysics
ACIS	Advanced CCD Imaging Spectrometer
ACS	Advanced Camera for Surveys
ADAP	Astrophysics Database and Archives Program
AGN	Active Galactic Nuclei
ALIGO	Advanced Laser Interferometer Gravitational wave Observatory
ALMA	Atacama Large Millimeter Array
AU	Astronomical Unit

B

BAT	Burst Alert Telescope
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C

CANDELS	Cosmic Assembly Near-infrared Deep Extragalactic Legacy Survey
CCD	Charge Coupled Device
CIB	Cosmic Infrared Background
CLASH	Cluster Lensing and Supernovae survey with Hubble
CMB	Cosmic Microwave Background
Co-I	Co-Investigator
COS	Cosmic Origins Spectrograph
CTI	Charge Transfer Inefficiency
CXO	Chandra X-ray Observatory
CY	Calendar Year

D

DDT	Director's Discretionary Time
Deg	Degree
DM	Dark Matter
DoE	Department of Energy

E

eROSITA	extended ROentgen Survey with an Imaging Telescope Array
ESA	European Space Agency
EVLA	Expanded Very Large Array

F

FGS	Fine Guidance Sensors
FOT	Fermi Operations Team
FOV	Field of View
FSSC	Fermi Science Support Center
FTE	Full Time Equivalent
FTOOLS	General and mission-specific software tools to manipulate FITS files
FUV	Far Ultra-Violet
FWHM	Full Width Half Maximum
FY	Fiscal Year

G

G	Green
GALEX	Galaxy Evolution Explorer
GBM	Gamma-ray Burst Monitor
GeV	Giga-electronVolt
GI	General Investigator
GO	General Observer
GOF	General Observer Facility
GSFC	Goddard Space Flight Center
GTO	Guaranteed Time Observers
GRB	Gamma-ray Bursts
GW	Gravitational Waves

H

HAWC	
HDF	Hubble Deep Field
HEASARC	High Energy Astrophysics Science Archive Research Center
HEASoft	High Energy Astrophysics software
HEMT	High Electron-Mobility Transistor
HETG	High Energy Transmission Grating
HFI	High Frequency Instrument
HRC	High Resolution Camera
HST	Hubble Space Telescope
HUDF	Hubble Ultra Deep Field
HXD	Hard X-ray Detector

I

IGM	InterGalactic Medium
INTEGRAL	International Gamma-Ray Astrophysics Laboratory
IR	InfraRed
IRAC	InfraRed Array Camera
ISAS	Institute for Space and Astronautical Science
ISM	InterStellar Medium

J

JAXA Japanese Aerospace Exploration Agency
JWST James Webb Space Telescope

K

K\$ Kilo Dollars
keV Kilo-electronVolt

L

LAT Large Area Telescope
LCDM Lambda Cold Dark Matter
LETG Low Energy Transmission Grating
LFI Low Frequency Instrument
LIGO Laser Interferometer Gravitational wave Observatory
LOFAR LOw Frequency ARray

O

OTFR On-The-Fly Reprocessing

M

M\$ Million Dollars
MAST Multimission Archive at STScI
MeV Mega-electronVolt
MIDEX Medium Class Explorer
MOS-1 Metal-Oxide- Silicon-1
MOS-2 Metal-Oxide- Silicon-2
Msec Mega seconds

N

NASA National Aeronautics and Space Administration
NExSci NASA Exoplanet Science Institute
NICMOS Near Infrared Camera and Multi-Objects Spectrograph
NOAO National Optical Astronomy Observatory
nm Nano-meters
NRAO National Radio Astronomy Observatory
NuSTAR Nuclear Spectroscopic Telescope ARray

P

PHAT Panchromatic Hubble Andromeda Treasury
PI Principal Investigator

R

R Red
RGS-1 Reflection Grating Spectrometers-1
RGS-2 Reflection Grating Spectrometers-2
RWA Reaction Wheel Assemblies
RXTE Rossi X-ray Timing Explorer
RYG Red Yellow Green

S

SED Spectral Energy Distribution
SKA Square Kilometer Array
SM4 Servicing Mission 4
SM Servicing Mission
SN SuperNova
SNR SuperNova Remnant
SR Senior Review
SR2010 Senior Review 2010
SRC Senior Review Committee
STIS Space Telescope Imaging Spectrograph
STScI Space Telescope Science Institute
Submm Sub-millimeter
SZ Sunyaev-Zel'dovich

T

TDA Time Domain Astronomy
TDRSS Tracking and Data Relay Satellite System
TeV Tera-electronVolt

U

UDF Ultra Deep Field
US United States
USD United States Dollar
UV Ultra-Violet
UVOT UV-Optical telescope

V

VERITAS Very Energetic Radiation Imaging Telescope Array System
VHE Very High Energy

W

WFIRST	Wide-Field Infrared Survey Telescope (WFIRST)
WFC3	Wide Field Camera 3
WISE	Wide-Field Infrared Survey Explorer
WMAP	Wilkinson Microwave Anisotropy Probe

X

XIS	X-ray Imaging Spectrometer
XRS	X-Ray Spectrometer
XRT	X-Ray Telescope
XSPEC	An X-Ray Spectral Fitting Package

Y

Y	Yellow
Yr	Year

Z

Z	red shift
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