The Keys to Successful Extended Missions

David A. Seal[1] and Emily A. Manor-Chapman[2]
Jet Propulsion Laboratory, California Institute of Technology, 4800 Oak Grove Drive, Pasadena, CA 91109

Many of NASA's successful missions of robotic exploration have gone on to highly productive mission extensions, from Voyager, Magellan, Ulysses, and Galileo, to the Mars Exploration Rovers Spirit and Opportunity, a variety of Mars orbiters, Spitzer, Deep Impact / EPOXI, and Cassini. These missions delivered not only a high science return during their prime science phase, but a wealth of opportunities during their extensions at a low incremental cost to the program. The success of such mission extensions can be traced to demonstration of new and unique science achievable during the extension; reduction in cost without significant increase in risk to spacecraft health; close inclusion of the science community and approval authorities in planning; intelligent design during the development and prime operations phase; and well crafted and conveyed extension proposals. This paper discusses lessons learned collected from a variety of project leaders which can be applied by current and future missions to maximize their chances of approval and success.

I. Introduction

Most NASA missions nearing the end of their nominal mission lifetime are candidates for extension via a structural biennial Senior Review. This process has been in place since the 1990s (Voyager, for example, has undergone 11 senior reviews; the Mars Exploration Rover project is now preparing for its eighth), and is now formally applied to both Earth and planetary missions alike following the formation of the Science and Mission Directorate (SMD) of NASA in 2004. To be approved for a mission extension, each project must answer a call for proposals with a detailed description of the scientific benefits of extension, plans for operating the mission, health and operability of space and ground assets, and the costs of continued operations. Also relevant are the plans for continued education and public outreach (E/PO).[1] Often projects are supplied with guidelines (financial limits in particular), formally or informally, from their representatives at NASA headquarters, representing the expectations of the customer of the scope of the proposal based on discussions and technical interchange with the project leading up to the Senior Review process. Each proposal is thoroughly reviewed for its scientific merit and feasibility by a multidisciplinary panel whose charter is "to maximize the scientific return from these programs within finite resources."[2] The most recent Senior Reviews have consolidated the proposal process into a single multimission senior review whose purpose is to "provide the best balanced science for the scarce available funding."[3]

Historically, most candidate missions (over 80 percent) are approved for some level of extension. However, some missions have been cancelled, and the level of support given to extensions depends on a number of factors, all of which are considered important but whose influence varies depending on the mission and circumstances. The Senior Review process must be taken as seriously as that of proposals for new missions, and a well-written proposal armed with strong arguments is crucial to a successful extension, regardless of the perceived success of the project during its prime mission. In many areas, the groundwork for approving an extension is laid during prime mission.

II. The Senior Review Process

The objective of the Senior Review process is to identify those missions beyond their prime mission lifetime whose continued operation contributes cost-effectively to both NASA's goals and the nation's operational needs, and identify the appropriate funding levels for those missions.[4] It is clearly stated in all recent Senior Review guideline packages that the overall scientific potential of the extended missions is paramount. However, acknowledgements are also made for a number of related factors as well, and details on a variety of issues comprise important subsections of each review proposal. These factors include:

- Opportunities for unique and unanticipated science

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[1] Supervisor, Mission Engineering & Planning Group, Systems Engineering Section, Jet Propulsion Laboratory.

[2] Lead Mission Planner, Cassini Mission, Jet Propulsion Laboratory

- The uniqueness of the scientific investigation(s) compared to other sources of data on the same phenomena
- The importance of long-term data sets and overall data continuity through overlap; improvement in sampling via extended spatial and temporal coverage; and opportunities for synergy of multiple instruments (often via multiple spacecraft / missions)
- The recent (last 2-3 years) scientific advances of the mission, as reported via refereed journal articles and other means allowing for an assessment of productivity
- The contributions of mission data to advance the objectives of operational agencies such as NOAA, DoD, and the USGS
- The contributions of mission data to key NASA scientific endeavors as specified by the Decadal Survey, including fields of study acknowledged on a national or global level as of high value (such as climate change)
- The availability and usability of scientific data produced in the Planetary Data System (including past history)
- The extent to which the scientific community beyond the mission science team may conduct research with mission data, and the adequacy of financial resources provided to support the analysis of science data

Discussion of the above factors comprises the bulk of the science section requested in each proposal. Each package also requires discussion briefing the review committee on the background of the mission, technical feasibility, budget, and (in some cases) Education and Public Outreach (E/PO) programs. Most recently, the 2012 Planetary Science Division guidelines also required discussion on a 85% budget option, listing the scientific and technical scope reductions and associated risks with a 15% cut to the proposed extended mission budget. These same guidelines also enforced a 35 page limit to the proposal; other recent Senior Review guidelines have also enforced similar page limits.

These introductory, technical, budgetary and E/PO discussions (where requested) require commentary on the following issues:

- Overall status and health of spacecraft, instruments, and ground systems, including limitations as a result of degradation / aging, use of consumables, failures, and obsolescence
- High-level (at least) description of end-of life activities in compliance with NASA planetary protection
- Detailed breakdown of proposed budget, with labor, major equipment, and other expenses explained in sufficient detail to determine and justify the cost of each proposed task
- Parallel funding sources that are required for mission support, and status
- Identification and roles of international or inter-Agency partners
- Project management plan, including risk analysis
- Science traceability matrix
- Mission data product inventory (where applicable)
- Publication list and historical accomplishments with respect to mission objectives
- Planned E/PO activities, target audience(s) and reporting process

The Senior Review proposals for each family of missions - currently Astrophysics, Earth Science, Heliophysics, and Planetary - are formally reviewed by members of a review panel, each often with a primary reviewer and multiple secondary reviewers. Limited time oral sessions are scheduled at NASA headquarters, and the review panel then meets, often ranking the proposals formally on bases such as a "high/medium/low utility value"[4] or more frequently a "science per dollar basis"[5,6] based on the expected returns from each project. The panel submits this ranking in the form of budgetary recommendations and detailed discussion of strengths, weaknesses, and relevance to NASA and national priorities, upon which the highest levels of NASA management decide the missions' fates.

III. Historical Extended Mission Support and Scientific Productivity

As stated previously, historical support for extensions of NASA's mission set has been strong, with 80+% of proposals being funded at a level sufficient to achieve some or all of the extended mission objectives. Senior Reviews to date have led to the removal of only 10-20% of the weakest extensions, some of which had partial instrument failures or significantly reduced capabilities.[6] In the past, some missions ranked low were given an opportunity to resubmit proposals with improved cost effectiveness evaluated in a subsequent Senior Review. However, this reclamation process is no longer in place, so projects essentially have one single opportunity to fund each extension of up to two years.

Most of the Senior Review reports available explicitly state the panel's assessments of the strengths and weaknesses of each proposal. The most frequently assessed strengths of the missions recommended for extension, with particular focus on those missions most highly rated, are listed as follows.

- Uniqueness of data acquired compared to other available means, or means envisioned in the near or far future
- Clear science traceability to the Decadal Survey and NASA priorities, including contributions to date traced to likely contributions via the mission extension
- Breadth of applicability of data acquired, including new applications not envisioned for prime mission
- Data accessibility (often quoting access statistics)
- Synergy with other missions and/or ground-based studies
- Observed improvements in operations, exhibited by reduced cost and team sizes

In contrast, the most frequently listed weaknesses, with particular focus on those proposals not recommended for extension, are listed below.

- Inadequate quantitative demonstration of science gained, e.g. what specific improvements in understanding would result from extending the data set(s)
- Insufficient discussion of possible contributions to revolutionary discoveries, as opposed to incremental advances in areas already explored
- Insufficient distinction between the productivity of the prime mission and the added value of the extension
- Scientific productivity of the wider community (more from the data archive) outmatching the productivity of the mission teams (more from new observations), indicating the bulk of the current science is being done with existing rather than new measurements
- Observed lack of strong community interest in existing data or new results
- Excessively high operations costs (excessive instrument support costs are often highlighted) and no plan for cost reduction over time
- Insufficient budgetary detail and justification for some costs; lack of traceability of costs to science operations
- Lack of discussion of synergy with other missions, including operational use insufficient to serve other potential national needs

Both of the above lists trace closely to the Senior Review guideline topics listed in section II, as expected. After reviewing the many Senior Review panel reports, it seems clear that the project's ability to tell a compelling science story and justify its expenses via a well written proposal is equally as important as the true value of the science itself. It is imperative, therefore, that projects (NASA or otherwise) devote significant resources to crafting its proposals for mission extensions.

Figure 1 illustrates the funding profile of both prime and extended mission phases for a sampling of projects. As stated in one Senior Review report, "relative to the prime phases, missions in the extended phase are expected to reduce costs quite significantly"[7], and this figure bears this out. The funding profile with time is shown by fiscal year (FY), with year zero containing the prime / extended mission transition (often in mid-FY). The funding profile is expressed as a percentage of the maximum pre-extended-mission phase E costs computed in real year dollars. This approach may introduce some mission-to-mission inconsistencies, as each project's funding profile during phase E shows year-to-year variability. However, the point of figure 1 is to observe qualitative trends in extended mission funding profiles and it is adequate for that purpose.

Generally speaking, mission extension funding profiles tend to fall in the range of 20-60% of peak prime mission funding; proposals above that level can expect additional scrutiny from review panels. Cassini may be the lone exception, with its first two years of extension funded fully at the prime mission amount. However, these first two years (named the "Equinox Mission") were specifically pitched as a seamless, prime science extension at the same level of scientific intensity and mission optimization as the prime mission. As the Saturn environment is arguably the most target-rich in the Solar System, the additional science, both unique and repeated, was felt to merit equal funding levels. Starting in Cassini's extension year 3, and for the remainder of the second mission extension (named the "Solstice Mission"), the funding profile drops to a 70-80% range with a commensurate drop in scientific intensity and optimization.[8,9] Similarly, Galileo and Spitzer are among the lowest funded extensions. Both of these are attributable to significant limitations in their mission extensions: Galileo's resulting from the high-gain antenna failure, problematic tape recorder and resulting curtailments in its scientific program; and Spitzer's due to the exhaustion of cryogenic coolant, reducing the number of instruments from three to one. Galileo's high reductions were foreseen, in fact with full agreement from the project; it was implicitly obvious due to the spacecraft issues that a reduction to 20-30% of prime mission funding was a foregone conclusion. Spitzer made concerted efforts not only to reduce operations costs, but to capitalize on a newly conceived and compelling single-instrument scientific program with significant synergy with other missions, and is one of the brightest success stories in the suite of extended missions studied.

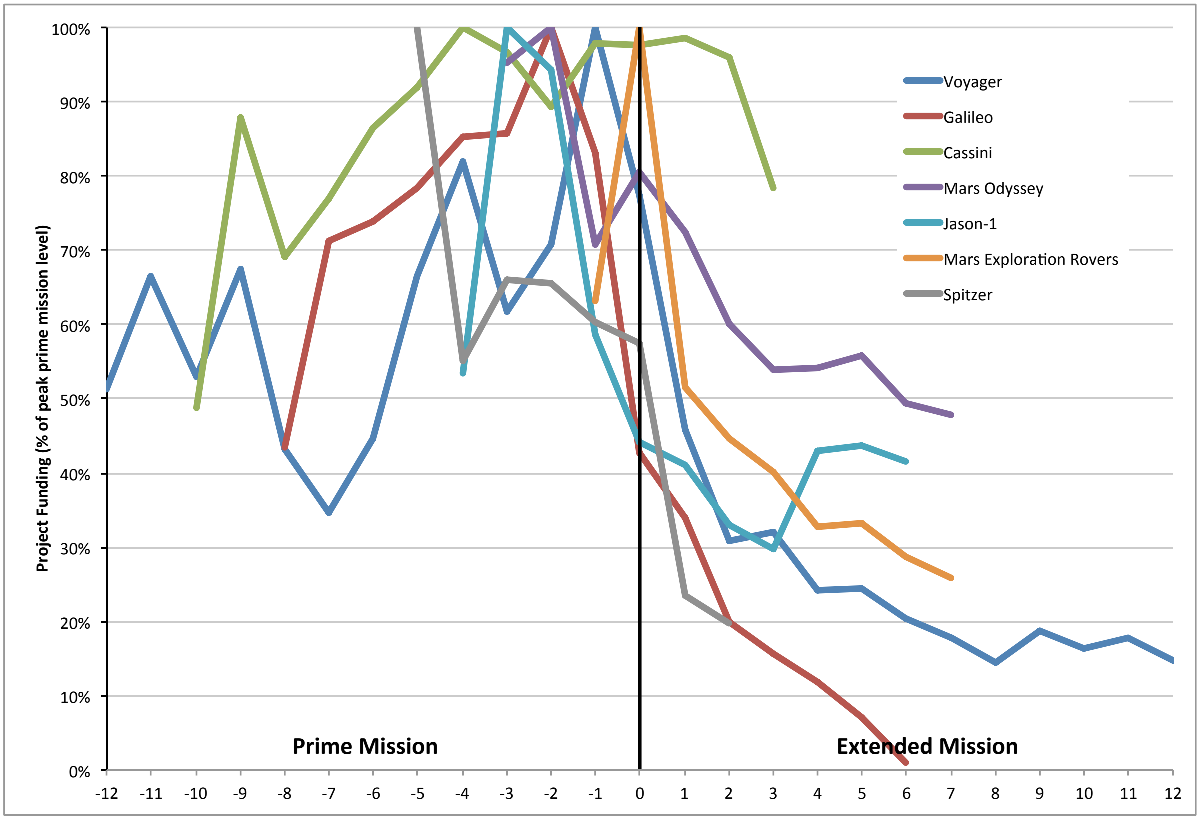

Figure 1. Project funding per year, plotted as a percentage of peak annual prime mission funding

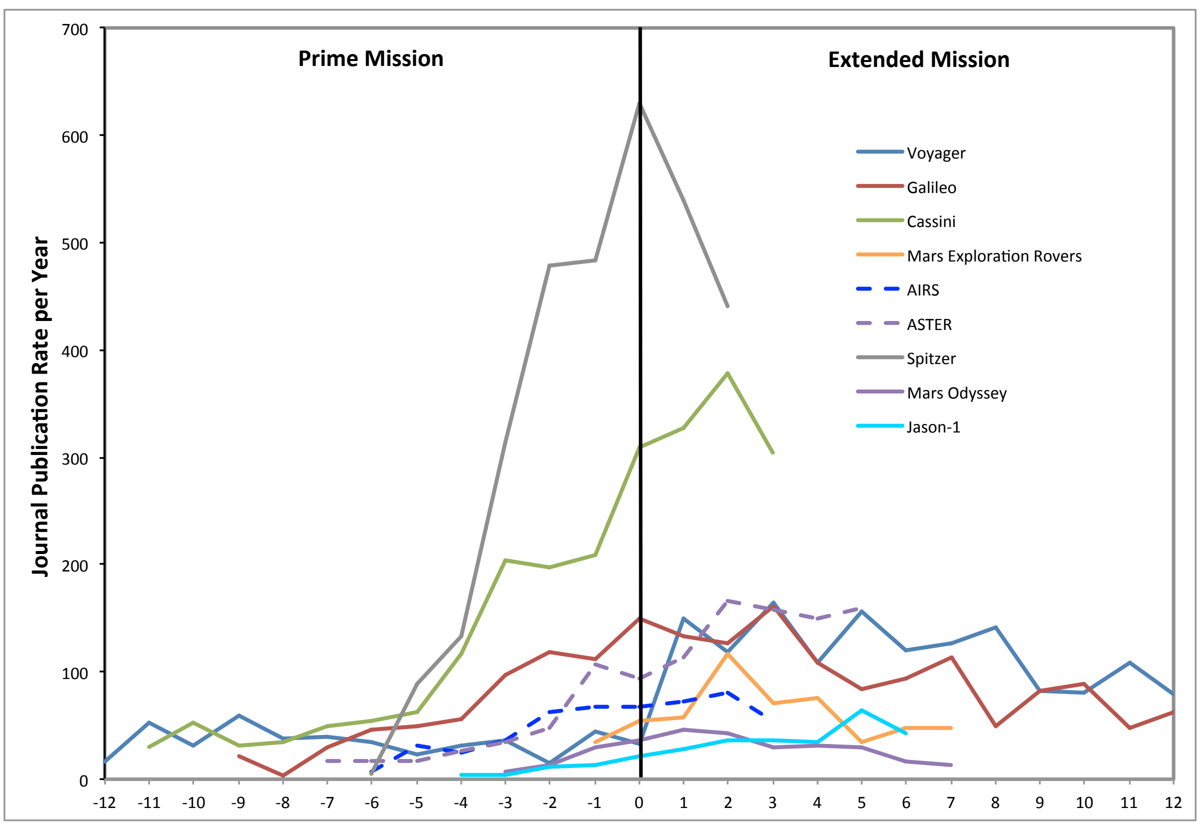

Figure 2. Journal publication rate by year for a variety of projects

Some projects show reduced operations costs before their mission extensions - Jason-1 and Spitzer in particular stand out in figure 1. Note that the Voyager (medium blue) funding level extends off the chart to the right, continuing at approximately the 15% level for many years.

Figure 2 illustrates the peer-reviewed journal publication rate by year for a similar variety of flight projects. Again, qualitative trends are the goal of figure 2, as an exhaustive search of all mission-related publications across all forums was not conducted. Therefore, one project's publication rate should not be compared against another assuming great precision. Also note that Spitzer year 2 and Cassini year 3 are incomplete surveys as publication statistics for year 2011 are not fully available as of publication of this paper.

Figure 2 does show the expected trend of increasing publications during prime mission as prime science data is collected. It is interesting to note that the publication rates do not noticeably slow in the extended mission phases, except after some years; it is not possible from figure 2 to distinguish between longer-term studies of prime mission observations (published after the end of prime mission), and short-term studies and discoveries enabled primarily by extended mission science. However, common sense and the authors' and solicited project leaders' knowledge of extended mission publications all favor the hypothesis that a significant fraction of the publications in the extended missions are enhanced or even directly enabled by extended mission measurements. It is straightforward to conclude that in terms of scientific productivity per dollar expended, extended missions represent the highest NASA return given their small incremental cost.

IV. Recommendations from Extended Mission Project Leaders

The authors engaged in detailed interviews of a dozen project leaders (project managers, mission managers, and project scientists; see Acknowledgements) whose experience spans a wide range of NASA robotic mission extensions across four decades, with durations of only a few months to over thirty years. Their lessons learned on the success of their extended missions, and of their experiences with the Senior Review proposal process are summarized below in seven key categories. No priority order is implied.

A. **Ensure the Scientific Program is Compelling**

Echoed by all project leaders interviewed was the need to assemble an exciting scientific program. This is obvious both from the instructions of the Senior Review proposals and from common sense. The "science story" is often the most discussed and analyzed portion of the proposal. With a solid case, the mission will sell itself.

Many project leaders were emphatic that *new and unique science* is paramount, among them Dr. Edward Stone, Voyager Project Scientist and JPL Director (1991-2001). "What's the discovery potential?" is a key question that must be addressed. Voyager survived two major threats to their continued program due to budget pressure, in 2000 and in 2004, after over a decade of quiet cruise since Neptune. The Voyager Interstellar Mission saw hints of the termination shock starting in 2002, and the fact that they were close to a wholly new environment, with high discovery potential of phenomena never before observed, was viewed as compelling and a major factor for extending the mission further. Both Deep Impact / EPOXI and Stardust / NExT also met with approval in part by repurposing missions to study entirely different comets (Deep Impact / EPOXI from Tempel-1 to Hartley-2 and Stardust / NExT from Wild-2 back to Tempel-1).

The GRAIL (Gravity Recovery And Interior Laboratory) project, only recently extended, also knew up front that their lunar science had to be unique for an extension to gain approval. There was little case to be made that further flight around the moon at the same altitude (55 km) would increase the knowledge of the gravitational field. Therefore, they opted to fly lower at half the altitude (23 km) and double the resolution of the gravity field measurements to a level of the crustal thickness, and this improvement opens up a variety of new fields of lunar study. Their proposal was arguably unique in that it was submitted before any prime mission science was even collected, due to the short prime and extended mission durations.

Spitzer may arguably be the best "dark horse" success story for new science during extension. Despite running out of cryogen, thus rendering two of three instruments unusable, they made a compelling case for continued and new observation strategies via devoting more observing time to single objects and collaboration with other observatories (Hubble, Chandra, and Kepler). In particular, the Spitzer proposal created a niche used to verify Kepler results that cannot be matched by other observatories, as Spitzer is the only infrared asset of its class currently in space. Spitzer's case was undoubtedly helped by the recognition of its target exoplanets and very distant (high-Z) objects of cosmological significance as hot topics in the Decadal Survey.

Many missions have pitched *seasonal coverage* as a lynchpin of a new science program, among them the Mars Reconnaissance Orbiter (MRO), the Mars Exploration Rovers (MER), Mars Odyssey, Ulysses, and Cassini. Ulysses based much of their extended science story on observations covering a full 11-year solar cycle. Similarly, Cassini devoted significant resources to arguing for an extension from northern winter solstice (shortly before arrival in 2004) to summer solstice in 2017, representing a full half season at Saturn, arguably covering the full range of geometric and environmental conditions. Illustration of these concepts was key to conveying such arguments.

Ulysses created visualizations of their science potential plotted in a circuit around the Sun; and Cassini illustrated their seasonal coverage - including that of previous visits by Pioneer and Voyager - in charts such as the one in Figure 3. The Saturn seasons (referring to northern hemisphere conditions) are illustrated, and the prime and "Equinox Mission" (2008-2010) are illustrated by blue and green bars respectively. The "Solstice Mission" now underway is shown by a yellow bar labeled "SM". Note the epochs of visits by Pioneer and Voyagers 1 and 2, shown as green diamonds (aligned with the previous Saturnian "year" above), indicating that only by continuing onto the Solstice mission could new environmental conditions be investigated. This illustration, and others like it, were used effectively to convey a unique environment for study with high discovery potential not likely to be achievable in the foreseeable future. Cassini's case was made strong by tying seasonal changes to phenomena across the target-rich Saturnian system, including the evolution of lakes near Titan's poles, variability of Enceladus' plumes, magnetospheric / solar wind interactions, Saturn's polar storms, and Saturn's ring structure (e.g. equinox offering unique illumination). Therefore it is not simply the claim of seasonal coverage, but concrete traceability of the resulting seasonal effects to new areas of discovery potential, that are scrutinized and favored by review panels.

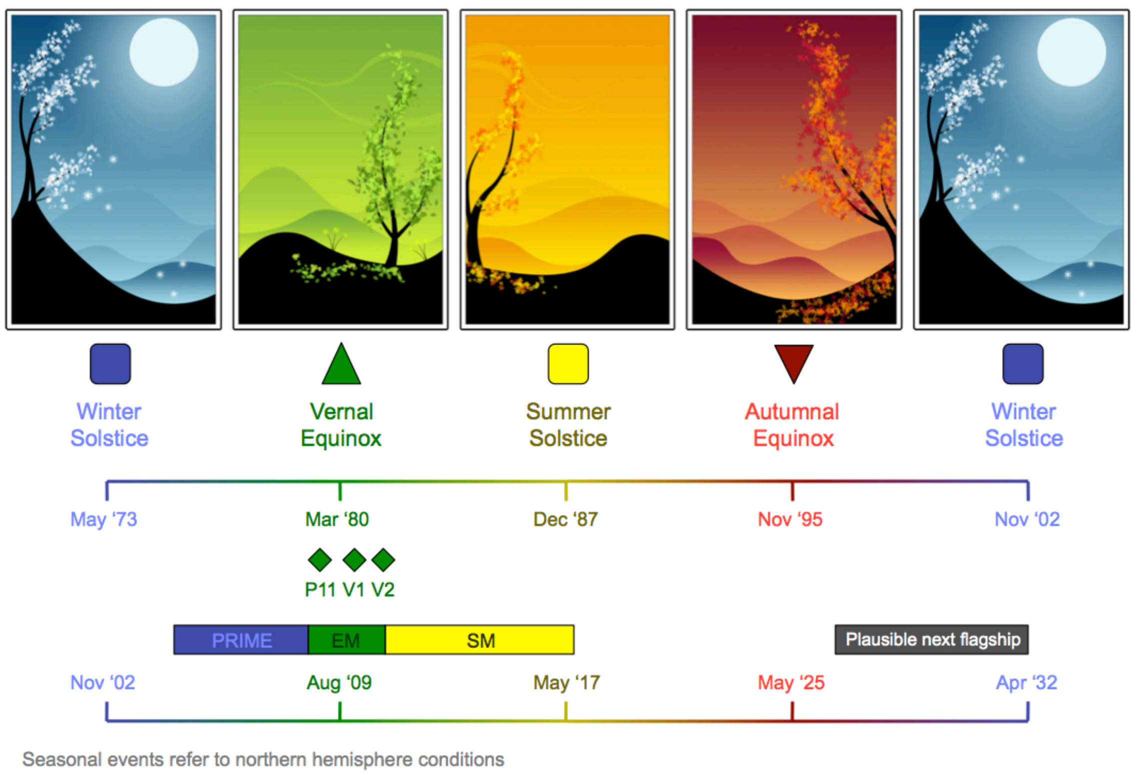

Figure 3. Saturn seasons and Cassini mission coverage (blue/green/yellow bars at bottom left)

For those missions whose new science may be a harder sell - true for some mapping missions, in particular - other arguments are available. Maintaining a continuous data record, and the reliance of other agencies on the asset's continued operation is valued. Jason-1 data is used during real-time operations by both NOAA and the U.S. Navy. Furthermore, Jason-1's applicability to climate change studies is acknowledged world-wide, and by the Intergovernmental Panel on Climate Change in particular. It's continued operation during the Jason-2 mission may not overtly lead to a new data type, but increases the resolution of the combined measurement set both spatially and temporally, leading to better observability of ocean phenomena. Similarly, the Quick Scatterometer (QuickSCAT) data set was acknowledged by the NOAA weather community as important, and has been used to cross-calibrate ocean satellite data acquired by spacecraft of the Indian space agency - not only a synergy argument but another example of an inter-agency connection as well. Along those lines, Ulysses' commitment of support by ESA in advance of NASA was also deemed likely to be a motivator for US support.

On the engineering side, Mars Odyssey represented the only UHF relay asset at Mars for some time (prior to MRO's arrival, at least) for missions such as MER, Phoenix, and the approaching Mars Science Laboratory, and its continued operation was deemed of critical importance as a fundamental link in the support chain to those missions. Nevertheless, Mars Odyssey also availed themselves of new science opportunities by changing their orbit geometry to map at new local solar time lighting conditions. Also, Magellan's last mission phase included cutting-edge aerobraking techniques and was deemed an important engineering demonstration for future missions.

B. **Build and Mobilize an Army of Proponents**

Preparations for extended mission proposals should begin, in most cases, at least 1-2 years in advance. Spitzer began conceptual design three years in advance, and concerted efforts 18 months before the estimated exhaustion of cryogen; Cassini had its first focused discussions on extended mission planning a full three years before the end of its prime mission. History has shown a high approval rate for extensions, and most project leaders described high confidence that their proposal would be funded at the time of their application. However, it is important to note that all of the project leaders interviewed were leaders of extensions that were successfully approved, and therefore leaders of future mission extensions that may be reading this paper and assuming confidence for their case would be guilty of drawing a conclusion from a biased data set. *Each project should prepare for a thorough scientific and technical assessment rather than a mere coronation.* Jim Erickson, project manager for the Mars Exploration Rovers, insisted emphatically that the entire Senior Review package must be well crafted to be successful in getting an extension approved.

Many project leaders also highlighted the need for the best writers and speakers to convey the proposal, going beyond the project office members at hand if necessary. The Spitzer project specifically brought in pundits outside its immediate management team to help pitch each of their three senior reviews. Voyager, GRAIL, Jason-1, MER, Galileo, Cassini, Mars Odyssey, and other proposals also benefitted, as described frequently during interviews, by dynamic project speakers who were known for their energy and communication abilities, including key science figures such as Drs. Ed Stone, Steve Squyres, Maria Zuber, Torrence Johnson, Tom Krimigis, William Patzert, Jonathan Lunine, Robert Pappalardo and Jeff Cuzzi. "And that could be the difference" - as stated by R. Mase, Mars Odyssey mission manager and Dawn Project Manager.

Spitzer also engaged its science community actively and early via workshops and even special sessions of AAS meetings used essentially as advertising. The project's "Science Opportunities for the Warm Spitzer Mission Workshop"[10] was held in June 2007 with 90 participants a full two years before the exhaustion of its cryogen supply, and its charter was designed precisely to gather the information required to compile a strong extension proposal: "the goal of the workshop was to identify these [cutting edge] science opportunities and consider how to best use the observatory in an efficient manner" [P. McCarthy, workshop chair]. This workshop, and the AAS sessions, not only equipped the project with ample ammunition to build a strong proposal, but it engaged the science community and strengthened their support for the extension by including them in its very planning, which paid dividends in perceived scientific support down the line. This approach was invaluable, and Spitzer's scientific productivity can be traced directly to these up-front efforts. The project's claim "to have one of the highest science return per dollar ratio of any of NASA's extended missions"[11] in light of its annual operating costs of one-third (or less) of the prime mission level is believable, especially considering the publication rate shown in figure 2. Other missions have adopted similar approaches, often lobbying the science community at general planetary conferences and workshops, and including PIs and other members of the science field in the proposal writing process and oral presentations to the Senior Review panels. Letters of endorsement from the science community are also useful and were solicited by a number of missions.

Communication with headquarters stakeholders and the approval authorities is also valuable; the support for a mission extension should be built ahead of time. Program executives and scientists should be made fans of the mission, engaged and excited. Posters and pictures of the mission and its scientific achievements should be on the walls of NASA headquarters. Project representatives should maintain a presence there and visit 2-4 times per year. In short, each mission, and its possible extension, should be consistently in the psyche of the stakeholders and decision makers. Furthermore, the project teams should do their homework on the target audience, the review panel specifically, to know what they're looking for and their fields of expertise. If the Senior Review panel can't understand the science plan or budget, or be made fans of the program of observations, as is reflected by their many comments in the weakness areas of some proposals, the odds of approval drop appreciably.

Lastly in this category, project leaders should leverage all resources available at their home center in compiling the proposal. If there are proposal-writing institutional resources outside the project, such as the project formulation sections and teams present at JPL, their expertise and review should be brought to bear. The success of any mission extension benefits the entire center.

C. **Revolutionize Operations Processes, with Continuous Improvements**

During prime science, much effort is spent optimizing the science data collection. Extensions must be prepared to operate less optimally, and realize significant cost savings for approval. Dr. Stone's advice was emphatic: be prepared to redesign your operations from the ground up. Spitzer led a complete review of all of its mission and science operations functions: "What do we no longer need to do? Can we merge teams? What are we doing right that we shouldn't change? What is 'good enough?'"[11] MER's rover leaders had similar experiences: "The operations process would need to transition from the high-intensity approach geared to wringing every possible bit of science out of the rovers in their presumed short lives to an approach that could be sustained indefinitely."[12] Exceptions may include some mapping missions which do not always revolutionize their operations, if they can demonstrate that they are already efficient and conducted at a minimum support level. However, even Jason-1 made significant operations staff reductions starting in prime mission via automation, improved software, streamlined processes and procedures. They cut operator staff from 12 operators (supporting 24/7 shifts) to 4 and leveraged cross-training to ensure that no required expertise for managing the asset resided in one person alone.

Galileo completely redesigned their operations process to conduct targeted observations during only a small fraction of their orbit (periapsis ± 1 week) and was recast as a single-target mission (Europa). Cassini's Solstice Mission completely restructured sequencing and realized significant operational savings, in particular by reducing the number of overlapping sequencing processes that needed to operate at one time (each requiring its own support team). Voyager merged its spacecraft teams in the early 90s and employed a stepwise process to downsize, learning along the way, from 50 people at the start of the Voyager Interstellar Mission in 1990, now down to 12.5 persons since 2005. MER moved from co-located science teams at JPL to remote operations, and transitioned from Mars time to Earth time and stopped working most weekends (requiring fewer plans per week that were less complex, shortening the tactical process); they continue to make incremental improvements in procedures. MER's new operations process is enabled by separating those work days where the Mars and Earth rover times are similar, allowing the team to plan in lockstep, from those days where the downlink is later than 1pm local time, where the team no longer tracks the downlink and the schedule reverts to a normal 8am start time. On these latter days, called "restricted sols", the tactical team uses data which is older, and so operations are more restricted and less complex. This work shift pattern repeats every 37 Earth-days and is executed by a team size of 45 (60 when both rovers were operational), down from 200 during prime mission.

Many projects change their staffing profiles and "flatten" the project structure, reducing middle management in particular and deputy positions (including even the GRAIL mission, with the shortest prime and extended mission durations of mere months). Many "worker bees" and spacecraft subsystem experts drop to part time; some depart the project altogether but are kept on-call. This is best done carefully and via team sharing with other projects (conducted effectively in particular by Lockheed Martin for Odyssey spacecraft support). Often team sizes shrink (including science teams), but the leadership, presumably with the highest level of expertise, remains the same.

Operations improvements and reductions in scientific intensity are best conveyed in proposals with quantitative visualizations where possible. During Cassini's internal review of candidate extended mission tours for the Solstice mission, the project developed "activity intensity" charts, such as figure 4, illustrating the rate of scientifically intensive events, and therefore operations workload, as a method to compare operations costs with scientific advancement. These charts clearly showed an average reduction in intensity to a 50-75% level and were used directly to scope the operations efforts. Such arguments lent credibility to the "science per dollar" related discussions during the Senior Review process and strengthened Cassini's case for delivering continued groundbreaking science at a reduced cost while remaining operationally feasible.

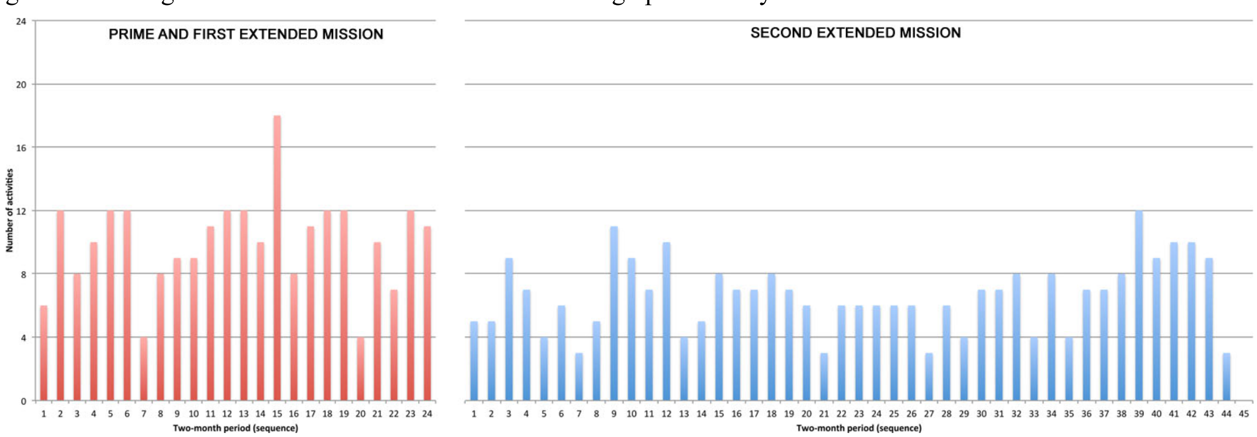

Figure 4. Cassini activity intensity, expressed as a number of intensive events per sequence

D. **Highlight Spacecraft Performance, and Maintain Low Risk to Spacecraft Operations**

Discussion of each project spacecraft's ability to continue operations appears nearly as often in review reports as the discussion of the scientific program. Possessing a healthy, well-behaved spacecraft is worth special mention in extension proposals; equally as important is a detailed explanation of how limitations in resources and the management of failed or glitchy systems will be handled. Robert Mitchell, Cassini project manager, stated of the mission extensions that "the fact that the spacecraft had performed flawlessly was a major factor in being able to do what we did." John Callas, MER project manager, echoed that the quality of their vehicles was very important: they survived Martian seasons and dust storms, and climbed steep walls, each of which were never envisioned for the original three month prime mission, and all of which were possible despite a relative lack of redundancy compared to most JPL spacecraft. The MER rovers were designed for 1 km of surface driving and have, as of the publication of this report, traversed 42 km (the combined total). Similar statistics can be quoted for all missions of this report, again echoing the conclusion that the largest scientific and technical return can often be achieved via extended missions at a modest investment.

Each of the proposals surveyed in detail provided explanations of how the project aimed to handle its aging hardware and prove that continued operations were possible. Ulysses had to prove that their power supply was sufficient for two more orbital circuits in both best and worst cases, as well as how the unexpected nutation from the axial boom would affect data return and "science fuzziness" from the resulting reduced knowledge of the spacecraft attitude. Magellan had significant anomalies in both strings of its transmitter and tape recorder and lost the ability to transmit RADAR data altogether in 1992 (transitioning as a result to a gravity mission). GRAIL's extension proposal was met with significant skepticism in light of their original claims that their spacecraft would not survive the lunar eclipse, and was an intensely discussed topic at their Senior Review oral presentation. Voyager 2's scan platform, which jammed at Saturn (attributed to overuse at its top speed), required rolls and turns be inserted in the science plans for Uranus and Neptune.

GRAIL's case deserves further mention. After flight trending and analysis, the project discovered that their spacecraft temperatures would not go outside of flight allowable limits during lunar eclipse, as opposed to what was believed prelaunch and conveyed as a mission-ending event. In this and other cases, limiting spacecraft resources and circumstances analyzed preflight are found to be not so limiting in the actual mission. Cassini has benefitted significantly from only having used *half* of its hydrazine attitude control propellant from launch through the end of the prime mission. Frequently, significant resource margins can be found via detailed analysis by the flight team after they have operated the spacecraft which enable mission options never before considered. In Cassini's case, the leading scientific argument for its final mission extension - in addition to seasonal coverage to northern summer solstice mentioned previously - is the ability of the spacecraft to fly *between the rings and the planet* on 22 passages. This orbital geometry and resulting unique science opportunities were never envisioned from development through even the end of prime mission, constitute essentially a wholly new Juno-like mission concept that itself would have been worthy of its own project, and was enabled primarily by the availability of significant flight resources combined with an experienced and skilled trajectory design team.

Without exception, all of the projects investigated opted to *take no additional risk to their space assets*, except where unavoidable (e.g. MER rover age and exposure to harsher conditions in the Martian environment, GRAIL's entrance into a thermally challenging lunar eclipse). Spitzer's number one guiding principle for its warm mission was blunt: "Don't do anything stupid"[11]. The no-additional-risk approach is not always applied to science data collection; Cassini, for example, cut back on some data saving techniques and other approaches aimed to preserve the most important data. Science bits are slightly more likely to "hit the ground" uncollected. Spitzer likewise also accepted this fact with similar bluntness among its guiding principles as well: "Accept additional risk to science".

Personnel turnover is a frequent occurrence during extended mission and can incur increased risk to operations without awareness and advance planning on the part of the project. Galileo asked for statements of intent from its personnel - not signed contracts, exactly, but commitments to work for a full two years of its mission extension - and got them. The stability of staff has been a big benefit to Cassini, and the risk of loss of key personnel was tracked explicitly as a project risk. Ulysses performed cross-training and rotation of roles to ensure that the team could survive personnel losses. Deep Impact / EPOXI faced a significant challenge in losing experienced staff between its encounters, but turned in part to early career hires to fill the gaps; though inexperienced, the projects gained innovation from these staff and they, in turn, gained experience and responsibility.

MER shortened their tactical planning cycle, required to release the team from working night shifts, by incremental automation of previously manual steps; the tools continued to evolve as the surface mission progressed; key functions performed by each team role were refined through experience, leading to elimination of nonessential tasks and better focused communications; libraries of reusable sequences were compiled and evolved; and complexity was reduced, especially with sequences that would necessitate intricate planning with low benefit to science.[12]

The loss of Mars Global Surveyor in November 2006, after operating at Mars four times longer than planned, also merits mention here. The operations review board concluded, in part, that "risks associated with normal personnel turnover over time were not assessed"; "procedures and processes were inadequate to catch the errors that occurred"; and "periodic reviews should have been performed to assure that spacecraft control parameters were appropriate" [13]. These quotes relate to the systems engineering of operations and the maintenance of processes and procedures, which was also mentioned by multiple project leaders. Suzanne Dodd, Voyager project manager, emphasized this as a key point: "the knowledge base evaporates with time." Current Voyager project members have expended significant effort to find and maintain project documentation, particularly those memos (many of which are translated from paper to electronic form) related to spacecraft behavior, trending, commanding formats, and flight software. Ulysses maintained subsystem handbooks for each position passed from one lead to another across its two mission extensions. These issues also bear resemblance to the breakdown in communications traced to other failures as well, and to the cultural problem highlighted by the Columbia Accident Investigation Board. Stephen B. Johnson, author of the article "Success, Failure, and NASA Culture" concludes that "80 to 95 percent of failures are ultimately due to human error and miscommunication. Most of these are quite simple.... The mundane nature of these causes is precisely what makes them so hard to catch." "Systems management and systems engineering reduce failure rates by providing formal cross-checks that find and fix most potential mission-ending faults." [14]

The identification of a minimum operating budget has been useful in some cases as a defense against budget starvation. Longer-term missions such as Voyager, which are considered "national treasures" and seem immune to cancellation by budget pressure, still require vigilance against being squeezed to death. Cassini, too, identified levels beyond which its spacecraft could not be operated without significant additional risk to the hardware. Cutting teams equally down to this level, and then describing the more severe cuts that would be required of the science teams having to bear all of the reductions alone beyond this level, was an illuminating argument during the Senior Review process. Mars Odyssey also focused project discussion on cutting to the minimally comfortable spacecraft team size; the science team size, as budget cuts were absorbed, stepped down during its mission extension, and it was not considered painless.

Last in this category is the issue of conflicts with other missions. Occasionally, projects' extended mission science is deemed to be a lower priority than the prime science of others. This has been exhibited - again, infrequently - in the loss of tracking passes and skilled personnel to other organizations. Voyager loses tracking passes to other missions with some regularity and cut their data rate to 160 bits per second in part because they didn't want to have to compete with primary science missions via high downlink requests. Their science collection is now a "take whatever we get" approach, purposefully designed as such, and arguably an outlier of the mission set studied. However, Cassini has also engaged in detailed negotiations beyond the norm on several occasions with other projects in an effort to assess their mutual conflicts and redesign its own science plans to stay out of the way as much as possible. Cassini even prepared justifications and successfully defended some key tracking passes that were more critical against loss to other missions, even near some missions' (e.g. Phoenix's) critical events where a typical result is the critical event gets all the tracking it needs without negotiation.

Extended mission project managers should also be vigilant of its personnel and reach out to their peers on other, newer projects at the same institutions to maintain an open line of communication, with the goal of not only the effective sharing of personnel - which can be a key component of low cost extended mission operations - but to ensure that the other projects are sensitized to the impact of their luring away an extended mission's most skilled and experienced staff members, which are often the first that are considered for key positions on projects earlier in their life cycle.

E. **Invest in Process, Hardware and Software Improvements**

In past decades, some projects have taken the approach that both flight and ground software, processes and procedures, and even ground hardware mature from a development phase during phase C/D and early operations to a quiescent maintenance phase, and should even be "frozen" across the board during prime science operations. This was thought to free up resources to focus on science gathering and simply a logical progression of ground and flight systems design. This approach is inherently flawed: projects must realize that software and process will always be evolving, and most project leaders in the current era recognize that a balanced level of development resources applied deep into prime mission is not only required but produces a clear benefit to the mission that is worth the investment.

Jason-1 in particular made a conscious effort during prime mission to expand the capabilities of their systems, not merely for bug fixes and consistency with changes in spacecraft behavior. Jason-1 leaders recognized that the small investment of development resources in prime mission would pay dividends down the line, not only later in prime mission, but during extension. Their efforts included consolidation of their hardware integration and test laboratory (ITL) to an all-software simulator after the prime mission. Other missions, including MER, have benefited from cost savings in extension of not having to maintain an aging ITL. One Voyager anecdote describes the project's acquisition of spare parts from military submarines for some aging but key computers used in soft simulation for sequencing, at least until after the Neptune encounter. Spitzer has improved their data compression and pointing performance via analysis, and these improvements bear benefits to science in addition to operations efficiency. MER continues to devote significant effort to modernizing their ground software and hardware, the use of cloud computing, and moving towards eliminating all ground test hardware. The result is a lower cost ground system which is more reliable and "greener" to boot.

All project leaders agreed similarly that multimission tool, OS and hardware upgrades should be adopted "as they come" at some reasonable level per year, without "freezes" or waiting to take them all at once.

F. **Manage Complacency**

Of the project leaders surveyed, about half believed that complacency simply was not a concern. Of those, all agreed that this was primarily due to the presence of stimulating analysis and replanning that was required during the mission extension; even the mapping missions have to accommodate changes in spacecraft behavior which keeps the teams busy and stimulated. Voyager was forced to update much of their planning due to lower telemetry rates, changes in lighting conditions resulting in different exposure techniques and the need for target motion compensation, upgrades to the Deep Space Network and resulting improvements to communications, and the loss of some Voyager 2 scan platform capabilities. Similar hardware issues on Galileo and Magellan occupied many analysis hours. Spitzer teams were kept busy by solar flares and the need to reevaluate power and geometry analyses. The uniqueness of each encounter and orbit makes planning on Cassini a consistently fresh experience as well; however, Cassini office managers are still reminded in quiet hours that they are responsible for keeping their teams sharp.

Other project leaders stated that complacency was a topic discussed often, with some missions having taken explicit steps against it. Jason-1 instituted regular retraining and requalification of personnel, and conducted simulated failures several times per year. MER is particularly vigilant against complacency: there are stand-down days and project retreats to address the concern, and the project deliberately puts “catch” items into plans to monitor team alertness. However, MER team excitement on the mission and science is believed to be high in general. Mars Odyssey, after 2001, began looking at commanding errors (also mandated by Lockheed Martin) to keep its staff sensitized to operations issues, and many missions now track this and other related performance data types frequently. In addition, Odyssey has a good inreach program and positive social gatherings that keep morale and motivation high. Cassini, as an indirect tool against complacency, also includes frequent inreach programs and regularly posts Cassini-derived “Astronomy Pictures of the Day” and other science images in its hallways.

It is imperative that Project and Mission Assurance Managers set a tone to new and seasoned operations staff alike to “be vigilant” with phrases such as “not on my watch”. Frequent inreach talks, articles, pictures, and interactions between scientists and engineers to share the exciting science being gathered can be useful motivators as reminders of the compelling reasons why the mission is being conducted.

G. **View Education and Public Outreach Program as Extended Mission Enabler**

NASA guidelines state that 1-2% of a project’s budget be used for Education and Public Outreach (E/PO). While many view this simply as a necessary (even fun) part of a project’s duties, not only as recompense for funding by taxpayer dollars but to inspire the next generation of engineers and scientists, E/PO is also an enabler for mission extensions if it is effective enough in translating the project’s accomplishments into the psyche of the nation and planet. The Hubble Space Telescope is easily the prime example of this; it has been stated in many publications that its servicing missions, particularly the last in May of 2009, were enabled not only by the outstanding science but as its place in the public as “the face of space science” and public outcry when its continued life was threatened. Voyager, considered a national treasure with its golden record (another outreach program altogether), is likely never to be canceled simply from budget pressure. Spitzer was at the forefront of the Myspace, podcasting, Facebook and Twitter revolution in social media starting as early as 2000, and their efforts to reach the younger community via these means were seen not only as part of the job but an investment in the project’s future, and the quality of future matriculating space scientists. Cassini’s Twitter feed now has the most followers of any NASA planetary mission in operation. Jason-1, whose products are seen all around the world whenever there is news of El Niño / La Niña, deliberately funded its E/PO effort *above* the NASA guideline, to the 3-4% level. The MER rovers are very popular with the public, and NASA headquarters clearly recognizes the public value of their continued operation.

Though it is impossible to quantify the effect of E/PO on extended mission approval, there is general agreement that it is a program worth specific mention in Senior Review proposals. Each mission must find the appropriate balance in funding, but the above discussion represents a new perspective on E/PO that should be considered, especially during the early mission phases. The participation of E/PO in Quarterly and Senior Reviews alike can also serve a dual role: not only do they communicate to NASA stakeholders the extent to which the mission is reaching the public (and the public’s perceived value of the mission itself), the outreach products shown are often as effective as exciting science results in converting those stakeholders into passionate supporters of the mission.

V. Conclusion

The Senior Review process is an effective one and the instructions to projects provide a thorough and equitable basis on which the proposals can be judged. The concepts herein, relevant not only during preparation of the extension proposal, but during the development of the prime mission priorities, represent lessons learned from project leaders across a wide range of applications and have the potential to increase a mission’s lifetime or its level of financial support during extension.

The authors can think of no more fitting closing than a recommendation of the 2012 Astrophysics Mission Senior Review panel: “It may be worthwhile to have a forum to share these [extended mission] 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 publicly accessible. There may well be design choices implemented during mission development that would allow for lower-cost extended operations after the prime phase.”[6]

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