

The Hubble-JWST Transition: A Policy Synopsis

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The Hubble Space Telescope has profoundly influenced virtually every prominent problem in astronomy, ranging from the nearest solar system body to the most distant observable objects in the Universe. In doing so it has also brought an unprecedented awareness of and enthusiasm for science in general, and astronomy in particular, to tens of millions of people. All of this success has been achieved through capabilities largely unrelated to the collecting area of the primary mirror. Indeed, at the time of launch, Hubble was approximately the tenth largest telescope in the world, and today it has fallen roughly to number 40 in the rankings. Rather, the combination of the vantage point afforded by its location 600 km above the Earth, combined with the ability to replace focal plane instruments periodically during servicing missions, thus taking advantage of the latest technology optimized to the most current problems, have given Hubble its amazing discovery power.

The Scientific Impact of Hubble

Almost any quantitative indicator of Hubble's scientific impact invites superlatives. In Figure 1 we display the number of refereed scientific papers resulting from Hubble observations as a function of year. At the close of 2002, the latest year for which statistics

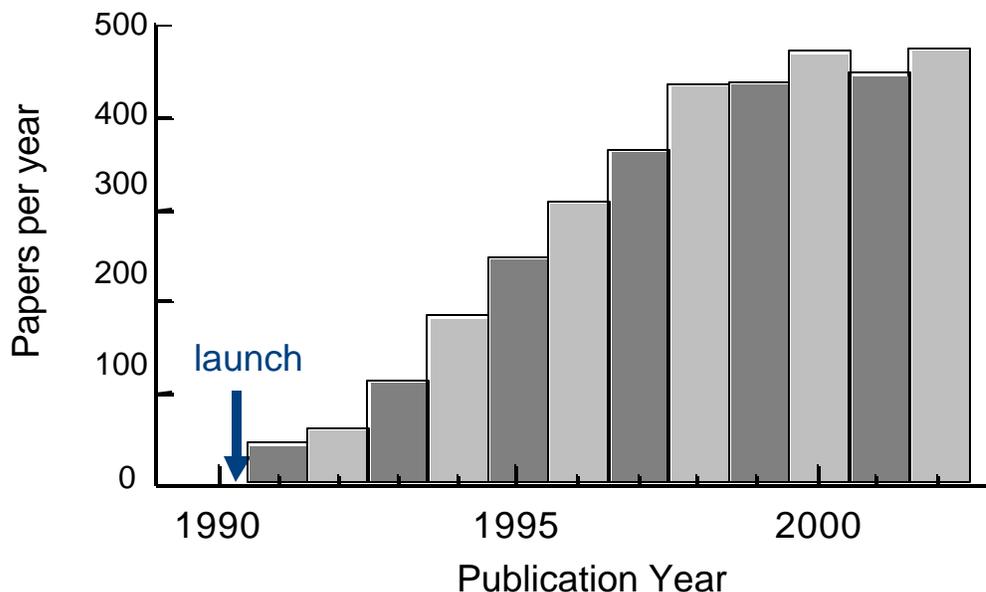


Figure 1

are available, almost 3,600 refereed papers have appeared. Perhaps equally interesting, the latest year was also the most productive. We are aware of no other NASA mission which is more than a decade old, yet grows more productive every year. As this survey

includes no results from the two most recently installed new instruments, the Advanced Camera for Surveys and the revived NICMOS, an infrared camera, we can confidently predict yet another increase in 2003.

An equally interesting metric on the impact of Hubble science is the fraction of refereed papers that depend on HST results in the most prestigious journals. We show in Figure 2 a survey of the fraction of papers in the five journals generally regarded as having the highest impact in astronomy, from each of four major, state-of-the-art, comparably ambitious observatories: the Very Large Array, the two Keck 10-m telescopes, the Chandra X-ray Observatory, and HST. In 2002, Hubble was responsible for almost 8% of all refereed papers in these five journals, regardless of topic or nation of origin, a fraction that exceeds each of the other facilities by a factor of two or more.

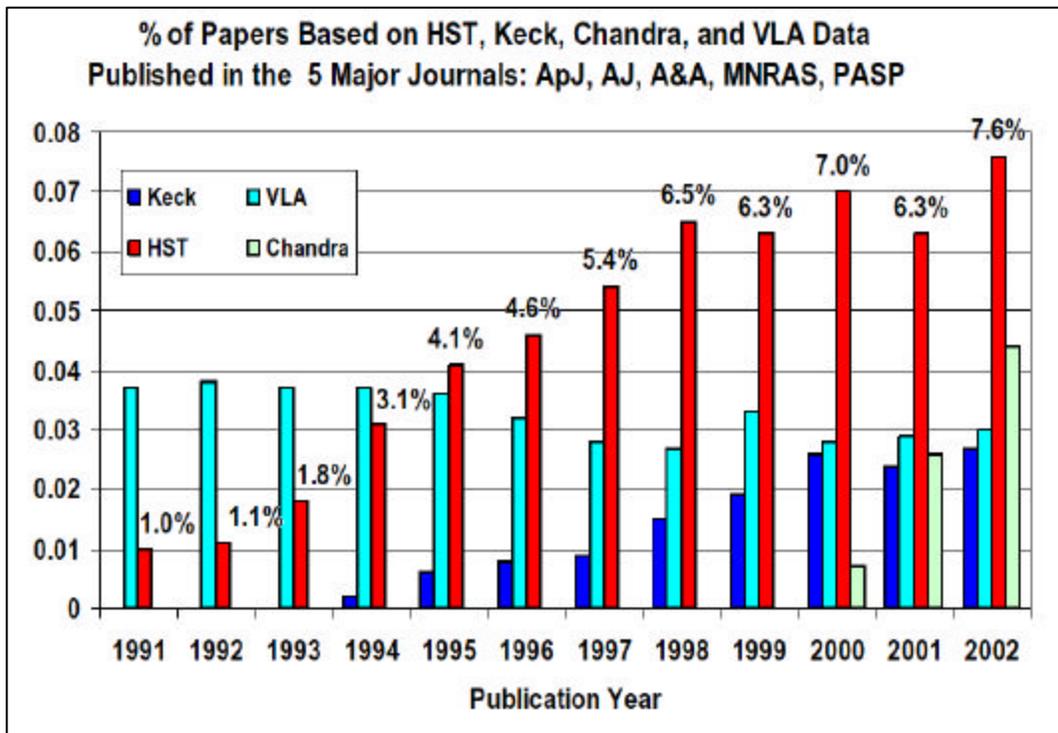


Figure 2

Finally, it is instructive to consider the oversubscription rate of proposals for use of HST from the community, and its evolution with time. We show these data in Figure 3. In the most recent time allocation cycle, the oversubscription was greater than 6-to-1, one of the highest factors in the 13 cycle lifetime of the observatory. (The factor for the previous year, cycle 11, was uncharacteristically high as that was the first year that very large “treasury” programs were solicited, and many exciting but unrealistically large proposals were submitted).

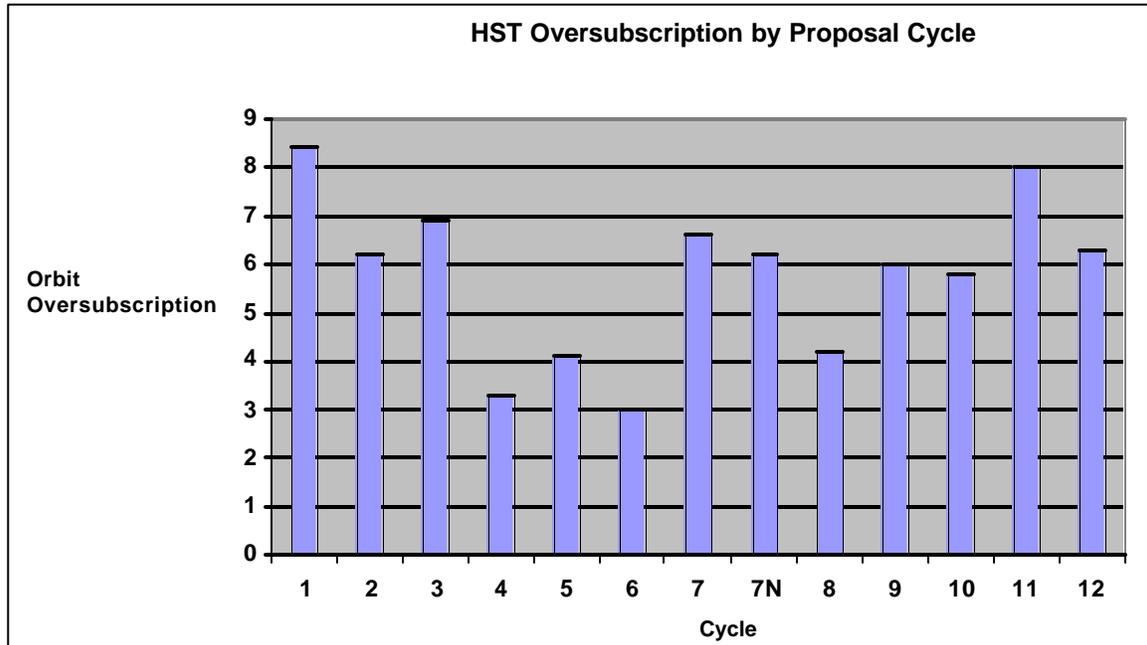


Figure 3

The Public Impact of Hubble

Astronomy has always been high on the list of sciences evoking public interest, but since the completion of the Palomar Hale telescope in 1948, no astronomical facility has achieved the international public prominence of Hubble. Part of this success is due to NASA’s vision in supporting a vigorous news and educational outreach program associated with the project, to facilitate dissemination of results. However the world’s attention cannot be retained for a decade on a physical science project solely by the efforts of a few public affairs and education experts, no matter how diligent.

Rather, it is the string of inspiring scientific discoveries from Hubble that account for the unprecedented success. We quantify this success briefly with two illustrations.

Figure 4 shows a survey of references in the Lexis news data base to astronomy news stories from a dozen major astronomical facilities in the past 12 months. The results show the remarkable interest in Hubble in its 13th year. Indeed, Hubble so dominates media interest that its popular citations constitute a large fraction of all science stories in all disciplines.

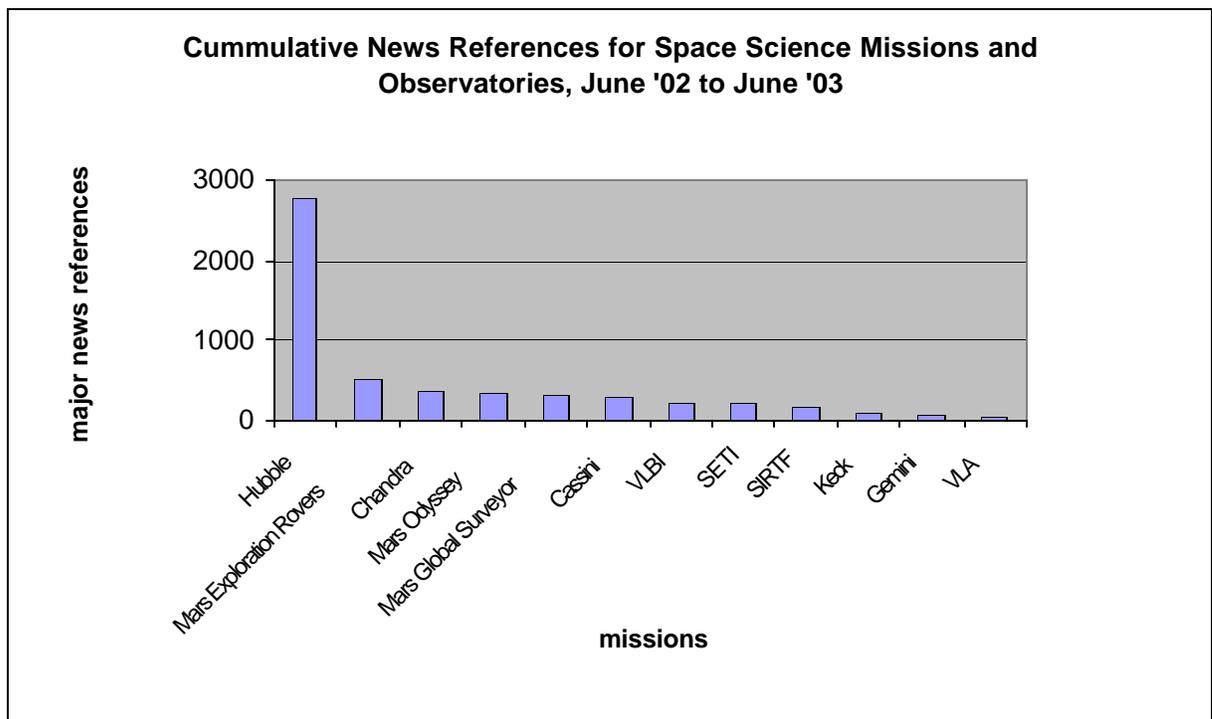


Figure 4

Figure 5 shows the latest results from the annual survey of science stories in the general interest weekly *Science News*, compiled by G. Davidson, originally at NASA HQ and now at Northrup-Grumman. The survey, conducted regularly for ten years, encompasses all science and technology coverage regardless of discipline or nation of origin. Hubble coverage in 2002 was 44% of all stories emerging from programs of the NASA Office of Space Science (more than double any other OSS project), and indeed 33% of all stories related to NASA in total (and thus even including all aspects of human space flight). The current annual operations budget of Hubble (dominated by the servicing mission staff at NASA Goddard Space Flight Center, but including also the development of new instruments, the Space Telescope Science Institute, and funds to the community for data analysis, archival research, education and public outreach grants, and Hubble Fellowships) is approximately 7% of the Office of Space Science, and 2% of the entire NASA annual budget. The cost effectiveness of Hubble's impact is clear.

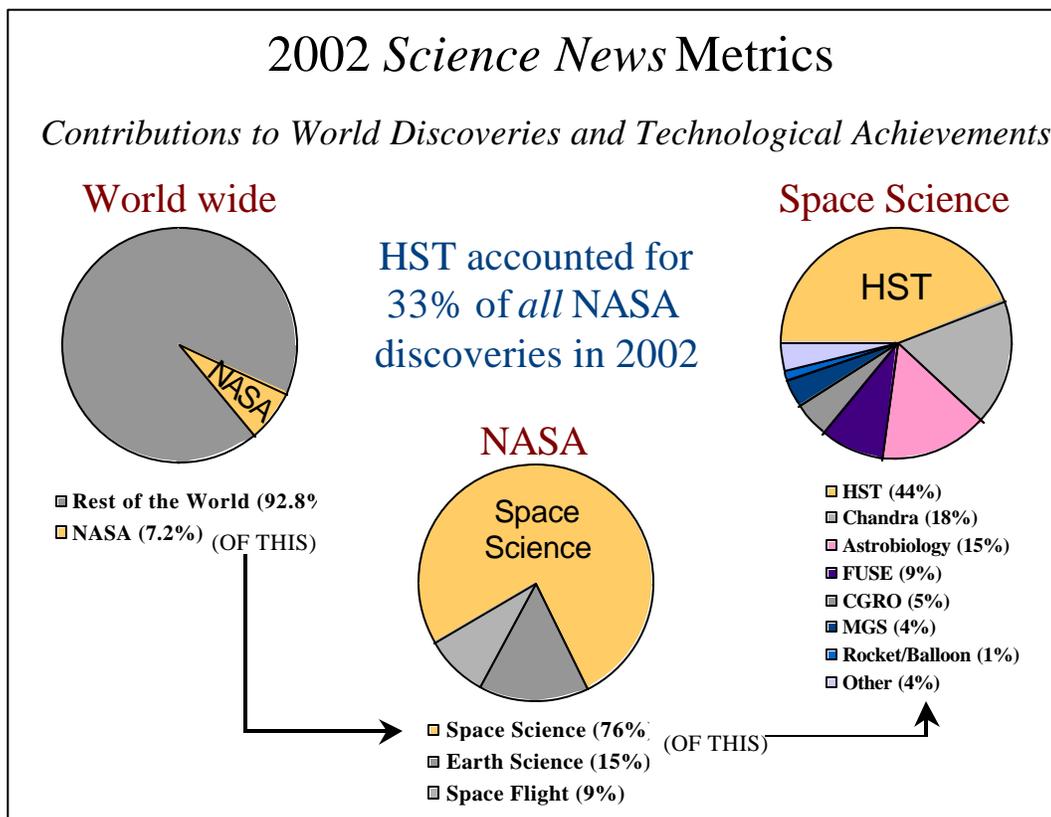


Figure 5

It is important to note that the public impact of Hubble is not simply in the area of news. The STScI conducts an aggressive program of dissemination of Hubble results in both formal education (primarily K-12) and informal education (museums, planetaria, internet, etc.). A few metrics on the results are instructive. The Institute's *Amazing Space* content package is currently used in more than 200 school districts, in all 50 states, for state school standards and inquiry-based learning methods, thereby touching several million students. It is also employed by more than 125 colleges of education to train teachers on principles of integrating technology into the curriculum, relating state education standards to inquiry-project based learning approaches. STScI has supplied more than 150 Hubble-based multimedia kiosks to science museums. The Hubble public outreach World Wide Web site (www.hubblesite.org) typically services 1 million distinct user sessions per month, comparable to the number of visitors to the National Air and Space Museum.

Servicing Hubble: Continuous Improvement in Science Capabilities

Servicing missions to Hubble are unique among space observatories in that they improve the capabilities of the telescope. Since the first visit in 1993, which restored the full resolution of the mirror, successive visits have increased the observing capabilities by between one and two orders of magnitude across the entire spectrum through the addition of new instruments. Even the maintenance tasks – replacement of solar arrays, computers, gyroscopes, power control units, and various upgrades to the shielding – serve to modernize the technology of the spacecraft and add capacity such as power, reliability, and data capacity. A servicing mission to Hubble is comparable in science value to the launch of a new satellite and should be judged as such.

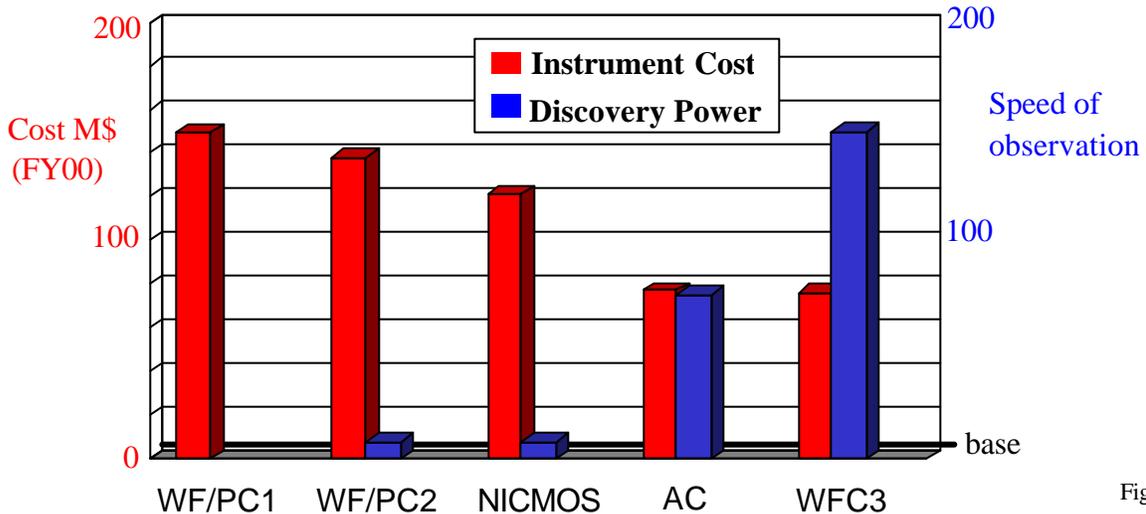


Figure 6

Figure 6 illustrates two aspects of this improvement program. The first is that successive instruments have improved the observational capability of imaging in speed, resolution, and wavelength coverage by factors of more than 10. Similar improvements have been made in the spectrographs (not shown.) The second aspect is that successive instruments have been constructed for substantially less cost than the original set. This remarkable

development results from the deep experience with the telescope that capitalizes on reuse of components and considerable certainty in how the interfaces will behave. Building instruments for Hubble entails low risk and very high scientific gain.

The Hubble Lifetime: Policy Issues

James Webb Space Telescope (JWST), the number one priority of the McKee/Taylor Decadal Survey, will be the flagship Office of Space Science project in the next decade, and probe in detail the most distant parts of the accessible Universe. NASA originally planned to operate Hubble until 2010 and launch JWST in 2007, providing a three-year overlap in science, and a comfortable cushion for delays in JWST. However, independent factors from both observatories now make any overlap improbable unless additional maintenance is performed on Hubble by astronauts late in this decade, in addition to that currently planned on SM4. The 13 years of HST operations have now provided a respectable empirical experience base on the expected lifetime of critical HST spacecraft components such as gyros. NASA has completed a detailed study that estimates and convolves the failure probability of key spacecraft and science instrument components (Figure 7). If the currently-planned final Servicing Mission, SM4, is launched sometime in 2005, a plausible but preliminary date based on recovery from the Columbia tragedy, the probability is then well less than 50% that HST will be returning useful science data in 2010.



Figure 7

Furthermore, the current launch date for JWST is August 2011, and even that date is in some doubt when judged by historical predictions for the other Great Observatories. Thus the gap between the end of HST science and the beginning of JWST science is likely to be 1 to 3 years, and could well be more. Therefore NASA's transition plan does not satisfy its earlier criterion that there be no gap, and some scientific overlap, in the operations of the two missions. Furthermore, the Columbia accident has caused a critical reexamination of how HST will be safely disposed of at the end of its lifetime, and places the current end-of-mission plan for HST in great doubt. Even early in this reexamination process *it has become evident that the new end-of-mission constraints may simultaneously present new, previously unavailable and relatively cost-effective options for preserving and possibly extending the scientific longevity of Hubble.*

In addition to possible overlap between HST and JWST, further criteria for setting the appropriate lifetime for a flagship program such as Hubble are surely the quality of expected science output in the final years as compared with other activities undertaken by OSS, as well as the cost-effectiveness of this science. Let us consider each of these three factors in turn.

Overlap with JWST. JWST is described in detail elsewhere in documents presented to the Bahcall committee. There are both similarities and differences in the capabilities and intellectual goals of the two programs. Although the primary wavelength regimes of the two telescopes are largely disjoint (UV through near-IR for HST, near-IR through mid-IR for JWST), the perhaps grandest scientific goals of both instruments are the same: to probe the very earliest phases of the universe accessible via observations of distant galaxies. Continuity in this scientific challenge is desirable. We note here that there are distinct and stronger drivers for continuity between the two projects.

- a) Decades of experience at multi-wavelength astronomical studies have shown that observations in visible light are often fundamental to understanding phenomena first explored at other wavelengths. Although some of these follow-up observations of JWST phenomena will surely be done from the ground, those requiring high angular resolution on faint objects over fields larger than a few arcseconds, and thus not accessible to adaptive optics, will require HST. Indeed, there may be entire new classes of problems stimulated by JWST results, and requiring HST for observation.
- b) In the time frame under discussion, HST will constitute the only significant aperture facility for ultraviolet imaging and spectroscopy, a crucial capability for many problems. For example, it has recently been appreciated that the so-called "cosmic web," the complexly-structured dilute gas between galaxies, in fact contains the dominant number of baryons in the Universe, and much of this matter is probed most effectively via ultraviolet spectroscopy.
- c) A high fraction of Hubble's scientific successes have been in areas not envisioned in the original design, yet still accessible to the observatory when required, e.g., photometric observations of distant SNIa to probe the acceleration of the

Universe, the Comet SL-9 impact with Jupiter, characterization of the host galaxies of gamma-ray bursters, the first spectroscopy of the atmosphere of an extrasolar planet, the first high-resolution images of circumstellar disks, etc. Thus there will always be significant discovery phase space for a space-borne large observatory, and a gap between HST and JWST operations will preclude the ability to discover new phenomena with HST, and to study those discovered by other facilities, especially those that will come on line near Hubble's nominal end-of-mission, such as Kepler, SIM, and ALMA.

- d) We have previously noted the enormous impact on public news and educational outreach enabled by Hubble, and we anticipate a comparable effect from JWST. But what large NASA project will carry the mantle in between, if there is a significant gap? The other Great Observatories, Chandra and SIRTf, will most certainly be inoperable in 2008 and beyond, and the launch of Terrestrial Planet Finder, Constellation-X, and the Einstein Probes will still be years in the future. There is nothing evident in NASA's plans that will maintain its current level of prominence in the schools and newspapers in the 2008-2012 timeframe.

Expected Science Output of an Extended Hubble Mission The scientific staff of STScI has, in consultation with the community, prepared an overview of predictable science from HST during 2010 and beyond, with and without new instruments, and that information will not be repeated here. It is evident from the huge current oversubscription of HST proposals (we receive a significant fraction of one decade worth of meritorious proposals each year) that we can continue to operate HST until JWST launch or beyond in the same mode as currently, that is, as a general purpose facility where the best peer-reviewed programs from the international community are selected, and we can confidently predict impact as profound as that described at the start of this document for the first decade of Hubble science.

It would also be possible to use HST in its later years chiefly or solely for one or two highly specific and important investigations. Two examples have been documented in detail in other materials supplied to the Bahcall committee: imaging of extrasolar planets via coronagraphy, and probing the Dark Energy through observations of a substantial number of distant supernovae. The former would require a new focal plane instrument; the latter would greatly benefit from one (a wide field imager), but substantial progress would be made with the already fixed post-SM4 instrument complement. It is beyond the scope of this document to contrast in detail the capabilities of HST in these areas. However we note the programmatic point that the SNAP (Supernova Acceleration Project) is a complex spacecraft (comparable aperture to HST) with extremely ambitious focal plane instruments, and at this point only in the concept stage. By contrast, the costs of operating and servicing Hubble are at this time well understood. Further, although it is indisputable that SNAP would observe a substantially larger number of supernovae than could HST, this advantage is dominant only if systematic uncertainty limitations do not intercede; predicting the latter is notoriously difficult.

Cost Effectiveness of Continued Hubble Science: Interactions with End-of-Mission Planning. It remains uncertain what the charge to the Office of Space Science for a “new,” Hubble-related, previously unplanned Shuttle flight would be. Regardless of whether an absolute or incremental charge is employed, however, it is clear that costs of any unplanned Shuttle flight to enhance Hubble longevity will be large.

The Columbia tragedy has substantially changed the notion of returning Hubble to Earth. NASA mandated long ago that Hubble under no circumstances be permitted to undergo an uncontrolled reentry at the end-of-mission. As there is no onboard propulsive capability, the options are either capture and return by the Shuttle, or adding propulsion to effect a controlled reentry or boost to permanent storage orbit. OSS has very recently stated in several public forums that, subsequent to the accident, the long-standing HST end-of-mission scenario, capture of HST by the Shuttle and return to a museum, is no longer plausible. The recently developed favored scenario appears to be adding a propulsion module.

Documentation on the propulsion module options has been provided to the Committee by NASA sources and will not be duplicated here. However an upper level review of the options is very relevant to the financing of a possible HST mission extension. If the propulsion module is not delivered by the Shuttle and installed by astronauts in a mission rather similar to a normal Hubble servicing mission, the only alternative is launch aboard an Expendable Launch Vehicle (ELV), followed by an autonomous docking with HST. NASA does not currently possess this technical capability, although there have been previous, now-terminated programs such as the Orbital Maneuvering Vehicle which have embarked on related development efforts, and thus may provide limited heritage. Further, unlike the International Space Station where Russian vehicles do autonomously dock, HST is an “uncooperative target”: it contains no onboard aids to the automated docking process. Therefore the ELV launch option will require substantial technical development, presumably with attendant cost and schedule uncertainties, and must be designed to a very high level of reliability if it is the primary plan to satisfy the mandatory “no uncontrolled reentry” directive.

We believe that the originally planned Shuttle mission to deorbit Hubble can be used to install a propulsion module with greater probability of success than an undeveloped robotic servicing capability. NASA’s astronauts have extensive experience and unqualified success working with Hubble in space, performing complex tasks not originally planned for servicing missions. Shuttles routinely carried propulsion modules for spacecraft at early times in the history of the program, and there is ample capacity to also carry other components, such as gyroscopes, to extend Hubble’s operational lifetime. At present, the most straightforward way to guarantee successful installation of a propulsion module on Hubble is through astronaut servicing.

Alternatively, if the development of a suitable propulsion module is sufficiently extended and difficult, a servicing visit by the Shuttle could be used to install cooperative docking aids for a later autonomous visit by an ELV, as well as to provide the now-routine altitude reboost to HST to extend the orbital lifetime, and permit a more leisurely

development and testing schedule for the propulsion module. An altitude boost of 10 nautical miles would guarantee Hubble's orbital lifetime to at least 2020, and with nominal solar conditions, beyond 2030.

The salient point here is that the costs of a Shuttle mission in 2010 have been part of NASA's plan for the HST-JWST transition for many years, and another visit to Hubble by the Shuttle post-SM4 may prove imperative to enable most or even all of the end-of-mission scenarios. One can view the cost of such a visit as "the same cost as the already approved museum return flight" or new funds which are mandatory to end the mission independent of any science considerations. In either case, it would be an enormous benefit to science to retain options to extend Hubble longevity and scientific capability for a Shuttle visit after SM4. The incremental costs to NASA's program will be less than the great incremental benefit to science, judged by the metrics presented above. Indeed, the most expensive part of preserving the possibility of these improvements, namely the servicing team at GSFC, will almost surely be needed for any visit to Hubble, even if only to install the propulsion module.

Summary

Determining the appropriate end-of-mission scenario for any ambitious and highly successful NASA program always requires complex tradeoffs. In the case of Hubble we have the added complication of strong interactions with the Shuttle program, whose precise future remains unclear at this time. Nonetheless it appears likely that any end-of-mission scenario will require substantial funds. *It should be a top priority of NASA and the community to reserve and foster all possible options that permit this expenditure to enable continued great science from Hubble wherever possible.* The history of Hubble thus far, and a modest glimpse at future HST investigations, shows that such extraordinary science is indeed awaiting the community if the spacecraft remains technically capable.

Hubble is unique among all current space science missions: it was designed to be maintained with an indefinite lifetime in orbit by shuttle-based astronaut servicing. By servicing Hubble every 3 to 4 years, we have the ability to take new technology to orbit on a regular basis, both for scientific instruments and spacecraft subsystems, thereby accelerating scientific discovery potential and maintaining a healthy, state-of-the-art spacecraft. The result of each mission is the renewal of a Great Observatory, a unique, strategic resource for astronomy and the public.

The Hubble Space Telescope is an amazing piece of equipment, and has seen more distant stars and galaxies than any telescope before or since. Earlier this year, it broke its own cosmic distance record by discovering a galaxy at a redshift of 11, back when the Universe was just 400 million years old. Yet the first stars should go back even farther, and Hubble will never see them. The reionization and star-formation history of our Universe. Image credit: NASA / S.G. Djorgovski & Digital Media Center / Caltech. Thanks to a combination of the fact that The Space Telescope Science Institute (STScI) has announced a Call for Applications to attend the James Webb Space Telescope (JWST) Master Class. The class will provide dedicated JWST proposal training to selected researchers who are willing to share their knowledge with scientists at their local/regional institutions. The original announcement from STScI can be found here. The European Space Agency (ESA) will provide a similar opportunity to European astronomers. A similar JWST Master Class will be organised at the European Space Astronomy Centre (ESAC) in the first week of February 2020. With all that the Hubble Space Telescope has done – including staring at a blank patch of sky for weeks worth of time – you might think there’s no limit to how far it can see. After all, what appears to be the physics of atoms, and of atomic transitions in particular, are the same everywhere in the Universe. Image credit: NASA / JWST science team. Whereas Hubble struggles to get to wavelengths as long as one micron, the James Webb Space Telescope (JWST) will get all the way down to about 30 microns with better sensitivity than anything else that’s come before, with better resolution and some six times the light-gathering power of Hubble! The space telescope that will take over from the Hubble observatory suffers a further delay. JWST will use a huge mirror and state-of-the-art instruments to try to see the first stars to shine in the cosmos. It will have the power as well to resolve the atmospheres of some of the new planets being discovered beyond our Solar System, and to analyse their atmospheres for the potential for life. Simulating and interpreting deep JWST/NIRSpec observations in the Hubble Ultra Deep Field. Jacopo Chevallard¹ , Emma Curtis-Lake², Stéphane Charlot², Pierre Ferruit¹, Giovanna Giardino¹, Marijn Franx³, Michael V. Maseda³, Ricardo Amorin^{4,5}, Santiago Arribas⁶, Andy Bunker⁷, Stefano Carniani^{5,6}, Bernd Husemann⁸, Peter Jakobsen⁹, Roberto Maiolino^{5,6}, Janine Pforr¹, Timothy D. Rawle¹⁰, Hans-Walter Rix⁸, Renske Smit^{5,6}, Chris. The James Webb Space Telescope (JWST) will enable the detection of optical emission lines in galaxies spanning a broad range of luminosities out to redshifts $z \sim 10$.