SPACE ASTRONOMY 2010-2015: THE ROLE OF THE HUBBLE SPACE TELESCOPE

Space Telescope Science Institute input to the NASA HST-JWST Transition Plan Review Panel
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ABSTRACT

The Hubble Space Telescope (HST) is one of the most productive scientific facilities ever built. Since launch in 1990 it has made fundamental contributions to nearly all areas of astrophysics, ranging from the solar system to the early universe. NASA has embarked on a critical examination of the timing of the end of the Hubble mission. This timing should be influenced first and foremost by the key scientific questions facing space astronomy and the tools needed to address them. HST's ability to contribute in 2010 or beyond depends on the continued health of the spacecraft and instruments, as well as on the potential for new instruments that could be installed. The cost of continued HST operations and even additional refurbishment must be weighed against other aspects of the NASA space-science enterprise.

This document identifies likely science contributions from HST in the early part of the next decade. Technical options for extending the HST mission are briefly reviewed. The issues of spacecraft health and survivability and the technological readiness of potential new instruments and new spacecraft subsystems are summarized with pointers to more complete documentation. Without refurbishment in $\sim$ 2009, there is a good chance that HST subsystem failures will leave the US without high-resolution optical or UV astronomy capabilities until at least 2013. A servicing mission in 2009 could upgrade the subsystems most prone to failure, boost HST high enough to delay re-entry until after 2020, and optionally install new instruments that would greatly expand HST science capabilities, and a propulsion module that would ensure a safe end to the HST mission.

1. INTRODUCTION

Since launch in 1990, the Hubble Space Telescope (HST) has made fundamental contributions to nearly all areas of astrophysics, ranging from the solar system to the early universe. It has accomplished many scientific goals originally envisioned for the mission: measurement of the Hubble constant, discovery of new planets and planetary systems, and exploration of the physics of the intergalactic and interstellar medium. It has also made observations and discoveries unanticipated at launch, among them identification of galaxies at very large redshifts, measurement of cosmic acceleration, identification of the hosts of Gamma-ray bursts, and observations of comet Shoemaker-Levy's collision with Jupiter. The HST servicing missions have brought order-of-magnitude increases in capability via new instruments and improved electronics. HST impact has gone well beyond the science community: its discoveries have captivated students, educators, and the general public.

The James Webb Space Telescope (JWST) will be the next leap in space-telescope technology, providing a logical continuation of many aspects of HST science. This mission was the highest-ranked project in the National Research Council's decadal survey of astronomy and astrophysics (McKee et al. 2003), and a number of scientific review committees since then have emphasized the importance of keeping JWST on schedule. The scientific capabilities of the two facilities are very different: JWST is diffraction limited at 2μm — the long wavelength limit of HST. While it will have a variety of imaging and spectroscopic capabilities longward of 1μm, between 1μm and its short-wavelength limit of 0.6μm, it will offer only wide-band imaging and very low-resolution spectroscopy. Image quality shortward of 1μm may not be significantly better than HST.

JWST and HST together account for roughly 12% of the NASA space-science budget in FY04, corresponding to roughly 3% of the total NASA budget. HST alone provides over 20% of the return in the NASA Space-Science program as measured by the Davidson Science-News Metric. Currently, the end of Hubble operations is planned for 2010, and the launch of JWST is planned for late 2011. Recognizing that critical decisions about the future of these missions must be fundamentally based on scientific considerations, NASA has chartered the *HST-JWST Transition Plan Review Panel* to review NASA's HST-retirement plan in the context of its overall space science program.

HST has been a remarkable engine of progress in astrophysics over the past decade. This document reviews a broad range of scientific topics for which

HST observations are likely to be critical in 2010 and beyond, with or without new instruments. Depending on the suite of instruments and the amount of time allocated, HST contributions could include some or all of the following:

- Detection of planets and characterization of planetary atmospheres via transits and microlensing light curves.
- Detection of sodium, water and carbon monoxide in the atmospheres of 5-10 extrasolar planets.
- Direct imaging and low-resolution spectroscopy of extra-solar planets.
- Determination of the nature of MACHO sources via microlens parallaxes and M31 microlensing measurements.
- Detection and mass-measurements of Milky-Way black holes — in globular clusters via proper motions and in the Galactic disk via microlensing parallaxes.
- Dating the onset of star formation in all galaxies in the Local Group via main-sequence turnoff photometry.
- Direct confirmation of dark matter in dwarf spheroidals through proper-motion measurements.
- Tests of galaxy-halo formation models using star counts to detect and statistically characterize tidal streams in dozens of nearby galaxies.
- Characterization of accretion flows near black-hole event horizons through reverberation mapping.
- Measuring the large-scale structure and physical conditions in intergalactic medium (IGM) at redshifts $z < 2$ through UV spectroscopy of quasar absorption lines.
- Testing whether galaxies form at peaks in the dark-matter density field via clustering measurements out to $z \sim 8$.
- Weak lensing measurements of the evolution of the mass and dark-matter density profiles of galaxies from $z \sim 2$ to the present.
- Determination of whether the dark energy represents a Cosmological Constant or a time-varying field using measurements of weak lensing (cosmic shear), large-scale structure, and type Ia supernovae.

Current schedules for major space and ground-based facilities suggest that HST will be the best facility available for such investigations until at least 2012 and probably for several years beyond. Signficant progress in some of these areas will be made through 2010, but many important investigations will be incomplete because landmark programs will require enormous investments of observing time. For example, with current instruments, measuring main-sequence turnoff ages for all galaxies in the local-group would require a full year of observations (4000 orbits). Detailed reverberation mapping of 10 active-galactic nuclei (AGN) would require a similar investment. Detection and monitoring of 200 supernovae at $1 < z < 1.6$ would require a year of observations. Nine months of observations would provide a measurement of skewness of the cosmological weak-lensing convergence field to a precision of 5%. A year of observations would measure the mass function of isolated black holes in M31 and the Milky Way. By 2010 HST will have done most of the easy things. The more challenging programs mentioned here either take much more time or require new, more powerful instruments. Either way, if it continues to operate, HST is likely to remain a keystone of astrophysical research well into the next decade.

The remainder of this document reviews various aspects of the transition from the HST to the JWST era. HST science topics for the early part of the next decade are identified and briefly discussed. (More extensive discussion of a few topics is provided by Fall et al. 2003.) Options for extending the HST mission are briefly reviewed. Aspects of spacecraft health and survivability, as well as the technological readiness of potential new instruments and new spacecraft subsystems, are briefly reviewed with pointers to more complete documentation.

2. THE HST MISSION

The HST mission so far is best summarized in terms of scientific accomplishments. While it is impossible to view the contributions of HST in isolation, given that advances in science often come from many directions at once, most would agree that HST has achieved much more than originally envisioned and fueled or critically supplemented many of the most important advances of the past decade. In many cases HST observations have taken a set of ideas from "speculative" to "proven," in others HST has dramatically improved the precision of a measurement. Amongst the highlights of HST contributions one can cite the following:

- Measurement of the Hubble constant;[1]
- Precise photometry of high-redshift Type Ia

[1] e.g. Freedman et al. (2001); Saha et al. (2001)

supernovae, providing evidence for cosmological acceleration;[2]

- Identification of galaxies at very high redshifts and measurements of the evolution of size, morphology, and stellar content of galaxies from redshifts $z \sim 6$ to $z \sim 0$;[3]
- Identification and characterization of quasar host galaxies;[4]
- Measurement of the evolution of the intergalactic medium via quasar absorption lines [5] and the HeII Gunn-Peterson effect;[6]
- The detection of the host galaxies of Gamma-Ray burst sources (GRBs);[7]
- Discovery of a correlation between black hole mass and galaxy bulge velocity dispersion;[8]
- Measurement of the stellar mass function in the Galactic bulge, halo, globular clusters, and star-forming regions;[9]
- Discovery and characterization of protoplanetary disks;[10]
- Identification of ubiquitous young star clusters in nearby star-forming galaxies;[11]
- Direct imaging of the accretion disk–jet connection in young stellar objects;[12]
- Detailed characterization of the morphology of stellar deaths;[13] and
- the detection of the atmosphere of a transiting planet.[14]

Instrumentation on HST has been upgraded during past servicing missions, in each case providing at least an order of magnitude improvement in some key area of scientific capability. Many of the technical solutions used in HST instruments have been at the forefront of current capabilities, conquering significant technology challenges (as reviewed by Tooley et al. 2003). The detector development effort has had a significant impact beyond HST — providing both technology and actual hardware for major instruments at groundbased observatories. A high-performance optical-IR camera and a sensitive UV spectrograph will be installed during the fifth servicing (SM4) scheduled for mid 2005. The suite of instruments and layout of the HST focal plane are shown in Fig. 1. Instruments deployed at HST's unique vantage point above the blurring, absorbing, and emitting effects of the Earth's atmosphere have kept HST, by now a small telescope relative to major ground-based facilities, at the cutting edge of observational astronomy.

2.1. *HST Status in 2010*

The shuttle servicing missions (SM) have successfully rejuvenated HST four times. The fifth servicing mission (SM4) is currently expected to occur in mid 2005. Instruments to be installed on this SM include the Wide-Field Camera 3 (WFC3), the Cosmic Origins Spectrograph (COS) and an upgrade of the third Fine Guidance Sensor (FGS3). Observatory systems improvements include an advanced cooling system, new batteries and gyroscopes, and repair of the multi-layer insulation.

Five years later the instruments are likely to be still operating reasonably well. Possible performance degradations are discussed by Tooley et al. (2003) and Black et al. (2003). The most serious concern is the non-redundant electronics in STIS. For the observatory as a whole the most serious concerns are the gyroscopes, needed for coarse pointing, and the fine guidance sensors. **Overall trends suggest a 50% chance that a hardware failure will make HST incapable of science observations roughly 4 years after SM4 (Tooley et al. 2003).** A servicing mission in 2009 would be in line with the previous servicing-mission frequency and would extend the mission by at least another four years.

2.2. *HST End-of-Mission Options*

NASA has funded a sixth shuttle mission to retrieve HST in 2010. A variety of options exist for extending the HST mission beyond 2010. Among them:

1. *"Rusty rails" operation.* Continue operating for as long as possible after SM4 subject to the operability of the spacecraft and instruments. This was in effect the NASA default plan prior to the Columbia accident. A 7 km boost in orbital altitude during SM4 (well within the feasible range for the shuttle) would be sufficient to postpone re-entry until 2020 even if the next solar maximum is stronger than normal.

2. *A robotic mission to add a propulsion module.*

[2] Riess et al. (1998); Perlmutter et al. (1999); Riess et al. (2001)
[3] reviewed by Ellis (1997) and Ferguson et al. (2000)
[4] e.g. Bahcall et al. (1997); Hamilton et al. (2002)
[5] e.g. Bahcall et al. (1993); Bergeron et al. (1994); Weymann et al. (1998)
[6] Jakobsen (1998)
[7] e.g. Sahu et al. (1997); Fruchter et al. (1999)
[8] Ferrarese & Merritt (2000); Gebhardt et al. (2000)
[9] e.g. Zoccali et al. (2000); Gould et al. (1998); King & Anderson (2002); Sirianni et al. (2000)
[10] e.g. O'dell et al. (1993); Heap et al. (2000)
[11] e.g. Holtzman et al. (1992)
[12] reviewed by Reipurth & Bally (2001)
[13] e.g. Sahai & Trauger (1998); Panagia et al. (1996)
[14] Charbonneau et al. (2002)

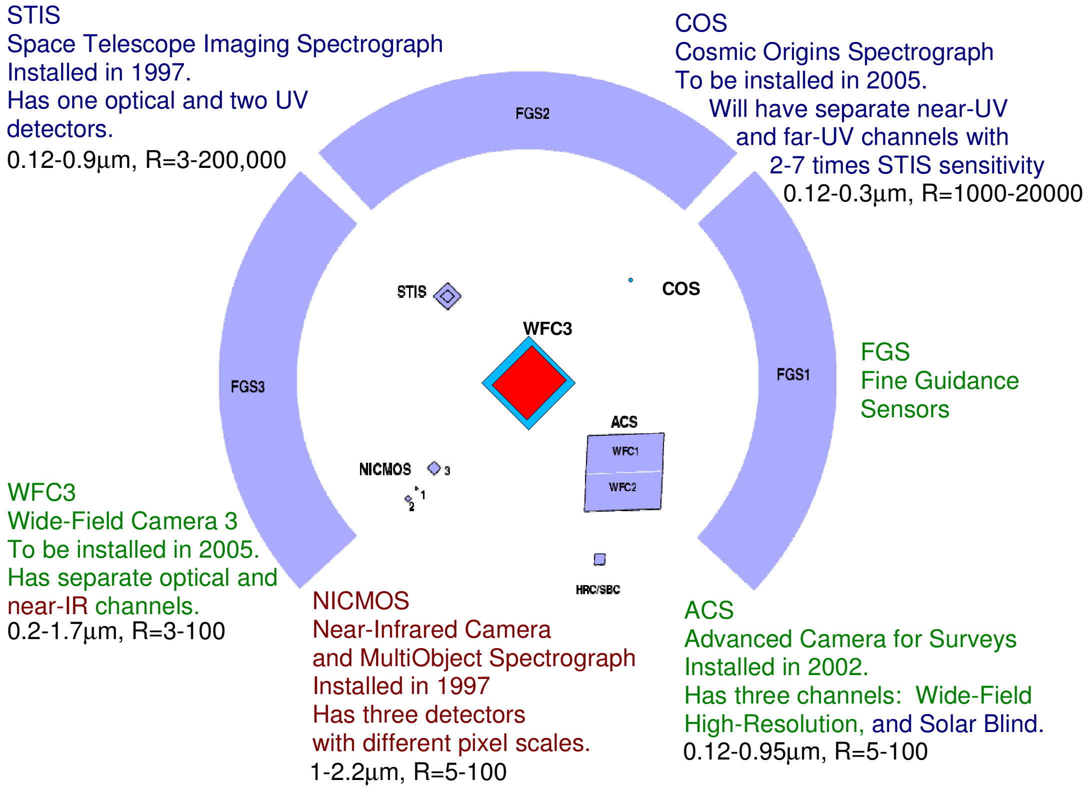

FIG. 1.— The HST instruments and layout of the HST focal plane after servicing mission 4 in 2005. The wavelength coverage and spectral resolution (R) is given for each of the instruments.

Attach a propulsion module to HST using an unmanned robotic servicing mission launched on an expendable launch vehicle. While such a solution would not provide new instruments or infrastructure, it would allow some relaxation of the levels of redundancy that would otherwise be required to ensure retrievability with the Space Shuttle. This could perhaps extend useful scientific operations beyond option 1. The propulsion module could either be used for a controlled re-entry at the desired time, or for limited reboosting capabilities during the scientific campaign.

3. *A further servicing mission (SM5).* Instead of retrieving HST in 2010, refurbish it in 2008 or 2009 and reboost it. A boost of 7 km in 2005 and 18 km 2009 would delay re-entry until 2032 if the next two solar cycles are typical. This servicing mission would replace the planned HST retrieval mission, and could optionally (a) install new instruments, and/or (b) install a propulsion module to allow safe re-entry of HST at the end of its useful life. If a propulsion module were not installed, a safe way to control HST re-entry would still need to be found, but the shuttle reboost would be sufficient to defer the necessary decisions for at least a decade.

If JWST were a direct replacement for HST and were unlikely to slip from its 2011 launch date, option 1 would be the most cost effective solution. If there were no way to delay HST re-entry until beyond 2020, option 2 would probably be the safest way to end the HST mission. **However, option 3 will undoubtedly yield the greatest scientific return and could either ensure safe re-entry of HST by installing a booster or defer re-entry far enough into the future that other technological solutions could be found.**

3. HST SCIENCE IN THE NEXT DECADE

HST is currently one of the most over-subscribed astronomical facilities: less than 20% of the 700-1000 proposals per year receive observing time. HST produces a very high rate of return as measured by publication and citation volume — far exceeding that of any other astronomical facility (Beckwith 2003). A key question is whether HST will continue to contribute at the cutting edge of astrophysics in the year 2010. While the pace of progress makes it difficult to predict which HST observations might have the most impact, there is little doubt (see §5) that even in the year 2010 HST will provide the highest available spatial resolution and point-source sensitivity in the optical and UV portions of the spectrum (1150Å to 1μm). In this section we outline possible major contributions from HST. We generally highlight areas that are considered high priorities in the 2003 NASA Origins and Structure-and-Evolution of the Universe (SEU) strategic plans or in the National Academy report on the boundaries of particle physics and cosmology (Turner et al. 2003). Many of these areas have seen significant progress since the drafting of the last decadal survey of Astronomy and Astrophysics (McKee et al. 2003) and in some cases the key questions or observational techniques have evolved.

HST contributions fall into three categories: (a) those that might be achievable with existing instruments without taking more than a few months of observations; (b) those that would require more than a year of observations with existing instruments (i.e. would displace most other potential projects to accomplish), and (c) those that would require new instruments. We focus here on the broad spectrum of HST science without going into specific hypothetical observing programs in detail. A few of these topics have been addressed in more detail by Fall et al. (2003). The combined requirement of even the projects outlined here is quite likely beyond what is possible in the remaining 28000 orbits of HST's nominal mission. As always, the appropriate observing priorities in these future years will be decided by the astronomical community through the peer-reviewed time allocation process.

3.1. *Structure and Evolution of the Universe*

3.1.1. *Cosmology, Dark Energy and Dark Matter*

Observations of the past decade have demonstrated convincingly that the dominant forms of mass and energy in the universe are in unexplained components. Dark matter constitutes roughly 30% of the mass-energy budget and is generally thought to be a fundamental particle that was non-relativistic at decoupling (Cold Dark Matter; CDM). Dark energy is the dominant component, $\sim 70\%$, and appears to be causing the expansion of the universe to accelerate at the present epoch. The rapid evolution in cosmology makes it difficult to predict which measurements will be the most relevant in the early part of the next decade. Indeed it is unclear whether the next breakthroughs will come from astrophysics or laboratory experiments. Nevertheless, were HST to continue to operate, it is likely that it would continue to contribute in important ways to our understanding of the dominant constituents of the universe.

The Friedmann equation relates the expansion rate of the universe $H(z)$ to the mass-energy density. The evolution of $H(z)$ in turn determines the age of the universe $t(z)$, the luminosity distance $d_L(z)$, angular-diameter distance $d_A(z)$, the volume element $dV \propto d_A^2(z)H^{-1}(z)$, and the growth factor of linear perturbations $D_1(z)$. For many purposes it is convenient to parametrize the effects of dark energy as a negative pressure with an equation of state $p = w\rho$, where w could be either constant or time varying (Caldwell et al. 1998; Ratra & Peebles 1988; Turner & White 1997). Current observational efforts to constrain the nature of dark energy focus on geometrical measurements as a means to constrain w and its first derivative with time w'. The sensitivity of the different parameters to w and w' are discussed by Kujat et al. (2002) and Tegmark (2002).

The nature of dark energy: high-redshift supernovae

Extensive observations with HST and large groundbased telescopes are underway to use type Ia supernovae to measure the relation between luminosity distance $d_L(z)$ and redshift. At a rate of roughly 10 SN Ia with $z > 1$ per year, representing about 10% of HST and groundbased telescope resources, we can expect greatly improved constraints on $d_L(z)$ by 2010. A more concerted investment of observing time with HST and major groundbased facilities would of course yield better constraints. Fall et al. (2003) outline possible programs with either the SM4 complement of instruments or a new wide-field imager. The SuperNova Acceleration Probe (SNAP) mission, if flown, would provide a sample of roughly 2000 SNe out to $z = 1.7$ with light curves and spectra. NASA's 2003 SEU roadmap targets 2012-2015 as the launch date for the first Einstein Probe, which could in principle be SNAP. HST could make great headway in these measurements earlier and at lower cost. The main sacrifices would be in the sampling of the light curves and the completeness of the spectroscopic confirmation. **Equipped with a sensitive wide-field imager, with one year of observations HST would be able to observe more than 1000 SNe up to redshifts** $z = 1.7$. The formal constraints on w and w' are comparable to SNAP (Fall et al. 2003). The massive multiplexing design of SNAP is envisioned as insurance to buttress the SN measurement against systematic effects (e.g., via sampling light curves at daily intervals). However, it is not yet known whether significant systematic errors exist, can be corrected, or will dominate the error budget (in which case a less ambitious sample of SNe might yield equivalent constraints). HST has some very attractive attributes as a precursor to an ultra-wide-field imager: it has a larger aperture and better image quality than SNAP, it exists and works today, and most of the infrastructure needed to support a camera with a factor of 10 gain in efficiency (through field of view or multiplexing) is already in place (pointing ability, power, thermal control, command and control systems, ground systems, etc.).

Complementary constraints on dark-energy and dark matter

There is a wide variety of other dark-energy probes under study. These include (1) using weak and strong gravitational lensing to constrain $d_A(z)$ and $D_1(z)$, (2) measuring $H(z)d_A(z)$ via the Alcock and Paczynski (1979) test using galaxies, QSO's, or the Lyman-α forest, (3) using unbiased cluster samples identified via the Sunyaev-Zeldovich effect to measure $d_A(z)$ and $D_1(z)$, (4) using galaxy ages to constrain $t(z)$, (5) using galaxy number counts to constrain $dV(z)$, and (6) mapping the acoustic peaks in the galaxy spectrum as a measure of $d_A(z)$. These tests provide constraints on w which may be competitive (and in some cases less observationally demanding) than SNe Ia. Constraints on w' from all techniques require more precision and it is as yet unclear which of the many techniques will prove the most powerful.

HST can contribute in important ways to these measurements. **HST sensitivity and resolution allow precise measurements of cosmic shear, free of many of the systematic effects that afflict groundbased surveys**. The statistics of the lensing convergence on scales of less than 10 arcmin are dominated by non-linear fluctuations, and are insensitive to the shape and normalization of the (CDM-type) power spectrum, depending almost entirely on the cosmological energy contents through their influence on $d_A(z)$ and $D_1(z)$ (Hui 1999). Ground based measurements are limited by the density of available galaxies on very small scales ($< 20''$), and by residual systematics on very large scales ($> 30'$). Due to the higher resolution and sensitivity, HST can probe effectively both extreme regimes, thus bridging the range between linear and non-linear growth of the perturbations. Important cosmological information is contained in the skewness and higher-order moments of the shear signal. A survey of 1 to 10 square degrees in multiple bands is conceivable with the HST SM4 instrument complement. Such a lensing survey would also be an excellent high-z supernova search tool, and would probe large-scale structure out to redshifts $z > 4$. Counts of carefully selected subsamples of galaxies will allow measurements of the volume element $dV(z)$ (Newman & Davis 2000, 2002). A more ambitious survey of 10 to 100 sq. degrees would be feasible if HST were equipped with an imager with 10 times the survey capability of ACS. Such a survey could in principle cover enough area to enable a measurement of $d_A(z)$ via the acoustic peaks in the the galaxy clustering power spectrum. Spectroscopy would be preferred over photometric redshifts for this measurement. HST could make important contributions here as well by providing grism spectra for objects that are difficult to measure even with 10-meter groundbased telescopes. **Finally, in the UV, HST will also constrain the evolution of the mass power spectrum through measurements of Lyman-α and Lyman-β forest clustering at $z < 2$.** Given suitable lines of sight from SDSS, the Alcock-Pacsynski test could be applied using Ly-α forest lines along the line of sight to close pairs of QSOs.

Fundamental physics

Microwave background experiments such as WMAP have revolutionized the precision to which our cosmological world-model can be tested. The precise constraints from the CMB measurements, and the perplexing nature of the cosmology that appears to be confirmed, now *increases* rather than decreases the need for precision in other measurements of the fundamental forces and constants of nature. For example measurements of the cosmic deuterium abundance and the variation of the fine-structure constant α would become vital as tests of fundamental physics if precision and systematic errors could be brought down by an order of magnitude. In the case of deuterium, the best measurements are for QSO absorption lines, but current observations show inconsistencies of nearly an order of magnitude, due largely to Lyα forest crowding at high redshift (Burles & Tytler 1998; Kirkman et al. 2000). Crowding problems are much less severe at lower redshift, hence UV spectroscopy is required (Pettini & Bowen 2001; Webb et al. 1997) Attempts to carry out this measurement with HST and FUSE have been limited by the lack of QSO's with known absorption systems of the appropriate column density, and the large integration times necessary to do the measurement. These problems will be solved in $\sim$ 2005 with the great influx of bright QSOs from SDSS and GALEX and the much higher sensitivity of the Cosmic Origins Spectrograph on HST. **An ambitious program, requiring ~ 6 months of telescope time, would survey ~ 1000 QSOs at low spectral resolution and S/N to identify suitable absorption line systems. Followup higher resolution spectroscopy of roughly 20 systems would reduce the random errors in D/H measurements to $\sim 5\%$.** Similarly, HST measurements will improve the precision of the many-multiplet technique (Murphy et al. 2003) for constraining the evolution of the fine-structure constant, α, by providing critical data for low-redshift absorption lines. Testing and controlling *systematic effects* in such measurements (of both deuterium and α) is critical and is a very active area of research.

3.1.2. *Dark Matter on Small Scales*

The favored candidates for dark matter on cosmological scales are long-lived, cold, collisionless subatomic particles (e.g. axions or neutralinos). Over the past several years a number of astrophysical problems with this hypothesis have emerged as vastly improved numerical simulations have confronted vastly improved data on the structure and kinematics of galaxies and groups of galaxies: (1) Milky-Way like galaxies appear to have too few companions and (2) galaxies and galaxy groups appear to have less dark matter in their centers than expected. Further observations will help to determine whether there is really a crisis in our understanding of dark matter on galaxy scales, and if so may help constrain the possible solutions (Ostriker & Steinhardt 2003). We focus here on lensing, but other observations (e.g. measurements of proper-motions of stars in dwarf-spheroidal galaxies) will also provide important constraints on the behavior of dark matter on galaxy scales.

The properties of dark-matter halos: weak lensing

Ground-based weak gravitational-lensing measurements from SDSS (McKay et al. 2001) have measured the dark matter density around galaxies in the local universe. **Lensing measurements with HST can measure the density profile at much smaller radii and establish the evolution of the dark-matter profile up to redshifts $z \sim 2$.** Such measurements directly trace the hierarchical evolution and merging of dark-matter halos and probe the mass and concentration parameter of dark matter halos in ways that can be compared directly to predictions of N-body simulations. Early results establish the viability of such observations, but also make it clear that a large amount of data — covering several square degrees in multiple bands — will be needed to measure how the properties of dark matter halos depend on those of visible light and how they evolve with redshift.

The properties of dark-matter halos: strong lensing

The positions of gravitationally lensed images (arcs) in clusters of galaxies — when combined with complementary mass measurements from kinematics or x-ray observations — provide a powerful probe of the profiles of dark-matter halos (Shapiro & Iliev 2000). N-body simulations and analytic models provide testable predictions for the relation between the central-concentration of dark matter halos, c, and their masses. Observations of roughly 100 lensing clusters would test both the mean relation and the predicted distribution about the mean — telling us whether clusters have the appropriate dark-matter core-radii for their masses.

The nature of MACHO events: microlensing

Seven years of monitoring of millions of stars toward the Magellanic Clouds by the MACHO and EROS collaborations have resulted in the detection of more than a dozen microlensing events toward the LMC and 2 events toward the SMC. There is much controversy on the exact nature of the lenses and there is, as yet, no consensus on whether the lenses are located in the Galactic halo, the local Galactic disk, or within the Magellanic Clouds. The exact contribution of MACHOs to the dark matter remains uncertain, and can be anywhere between 0 and 20% depending on where the lenses are located.

Measurement of the astrometric shifts due to microlensing can break the degeneracy and determine the distance to the lens. The expected astrometric shifts when the source is within the LMC, and the lens mass is 1 solar mass are 30 milli-arcseconds (mas) for a disk lens ($D_{lens} = 1$ kpc), 10 mas for a halo lens ($D_{lens} = 10$ kpc), and < 1 mas for a LMC lens. Such astrometric shifts are not measurable from the ground. With HST, the astrometric shifts in the first two cases would be clearly detectable. While some measurements could be carried out as followup observations of sources detected from the ground, an HST-based microlensing survey would detect fainter microlenses and measure parallaxes simultaneously. Observations of 50 ACS fields spaced every few days over four months (requiring essentially 100% of the telescope time in this period) would detect at least 10 events, for which astrometric shifts can also be measured if the lenses are MACHOs in the Galactic halo. Non-detection of the shifts would imply that the lenses are in the Magellanic clouds. If the lenses prove to be in the Milky Way, a comprehensive survey with a wide-field imager would allow a detailed characterization of the masses and spatial distribution of this dynamically important stellar population.

3.1.3. *Exotic Phenomena*

HST has made major contributions to our understanding of energetic phenomena in the universe through measurements of quasar spectra, identification of quasar host galaxies, monitoring of optical jets, monitoring of gamma-ray burst sources, and a wide variety of other observations. In this section we focus primarily on black holes and outline how HST in the next decade could be effective at finding and measuring the masses of black holes in a variety of environments.

The missing link: do intermediate mass black holes exist?

It is possible that black holes exist in the Universe with masses intermediate between those of the well-known stellar-mass and supermassive black holes. Such intermediate-mass black holes (IMBHs) might plausibly have formed as remnants of the first generation of stars (Population III; Madau & Rees

2001) or as the result of dense star cluster evolution (Portegies Zwart & McMillan 2002). Evidence for their existence is ambiguous (Baumgardt et al. 2003; Gebhardt et al. 2002; Kaaret et al. 2001). The possibility of finding IMBHs in the centers of globular clusters has long been of particular interest (Bahcall & Wolf 1976). Radial velocity work with STIS has not been able to unambiguously resolve this issue, but the long time baseline afforded by an extended HST mission offers the opportunity to trace stellar orbits in globular clusters directly using proper motions. One such program is currently underway by Drukier and collaborators. Observing requirements are very modest per cluster, but sensitivity increases as the time baseline increases.

The detection of isolated black holes

Microlensing provides the only known method which can be used to detect isolated black holes. About 1000 microlensing events have been detected so far toward the Galactic bulge, with timescales ranging from few days to many months. The events with timescales longer than 3 months are thought to be due to high-mass objects which are most likely black holes. However, the simple microlensing light curve is insufficient to provide information on the mass of the lens due to a well-known degeneracy between the mass, distance and the perpendicular velocity of the lens. Measurement of the astrometric shift can be used to break the degeneracy and determine the distance and mass of the lens. The expected astrometric shift when the source is within the Galactic bulge, and the lens mass is 1 solar mass is $32(m_{\rm lens}/D_{\rm lens})^{1/2}$ mas, where $D_{\rm lens}$ and $m_{\rm lens}$ are in units of kpc and solar mass, respectively. If a large number of microlensing events toward the galactic bulge can be detected with HST, the same HST observations can be used to measure the astrometric shifts as well. The combination of the photometric and astrometric measurements can be used to determine the masses of the lenses. With the milli-magnitude precision afforded by HST, general-relativistic effects may be detectable in the microlens light curves (Sereno 2003). HST can monitor roughly 10^6 bulge stars per orbit. **Based on observed microlensing rate, a 6-month to one year survey would discover and provide the masses of ~ 25 isolated black holes.** Observations of microlensing in M31 with a wide-field imager would provide another means of detecting isolated black holes. Light curves alone are sufficient since the distances are well constrained.

The physics of black-hole accretion: reverberation mapping

Gravitational accretion onto black holes produces a significant fraction (10-50%) of the radiation emitted by discrete sources over the history of the universe (e.g., Fabian & Iwasawa 1999). Understanding accretion processes is in a sense as important as understanding how stars shine. Reverberation mapping is a powerful technique for unraveling the geometry, emissivity and temperature in accretion flows. The temperature structure of the disk indicates where energy is released and how dissipative viscosity arises. Such measurements are necessary to understand the properties of the innermost region of the accretion flow near the event horizon. By making extensive observations of many sources, one can compare different AGN and Galactic sources. The velocity field and geometry of the broad-line region (BLR) can be determined uniquely by measuring the response to continuum variations (reverberation mapping), providing constraints on the central black-hole mass. Only from space can one obtain the spectrophotometric precision ($\sim$1%) required for the above experiments. The experiments are optimally carried out in the UV because the variations are stronger (in both lines and continuum), are undiluted by starlight, and have the shortest response times. To date, only a few AGN have been studied in this manner. A comprehensive study of 10 AGN would take roughly one year of HST time.

The demographics of black holes in normal galaxies

Measurements of the kinematics of stars and gas in the centers of nearby galaxies with HST have proven to be crucial in identifying nearby black holes and elucidating the relationship between black holes and host galaxies. An efficient integral-field spectrograph could improve the efficiency with which HST can study the nuclear regions of galaxies by an order of magnitude over STIS. This would permit a survey of a complete sample of nearby galaxies of all morphological types and a determination of the masses of their central black holes. Such a comprehensive demographic study will clarify the role played by black holes in galaxy formation and evolution, and reveal the dynamical signatures that determine nuclear activity in galaxies, control the fueling of central black holes, and trigger nuclear star formation.

3.2. *Origins*

3.2.1. *Cosmic Evolution*

HST has made major contributions to the understanding of the intergalactic medium. Highlights of ongoing research include tracing the ionization history and with the HeII Gunn-Peterson effect and the HeII forest (Jakobsen 1998; Smette et al. 2002) identifying an important reservoir of hot gas in the local universe through studies of OVI (Tripp et al. 2000), studying the relation between the IGM and gaseous halos of galaxies (Bowen et al. 2002), and studying the evolution of damped-Lyα absorbers and identifying their relation to galaxies. The installation of COS in 2005, combined with the discovery of hundreds of bright QSOs by SDSS and GALEX, will spark enormous progress in these areas. Nevertheless even with COS, building large statistical samples is painstaking work, which in many cases requires two cycles (e.g. a snapshot program in one cycle to identify suitable targets at low spectral resolution, followed by observationally expensive high-resolution spectroscopy in the next cycle).

Deep surveys with HST have also contributed to measurements of the overall star-formation history of the universe. HST sensitivity is required to identify and study typical $L < L^*$ Lyman-break galaxies at $z > 4$ and to measure rest-frame UV emission from galaxies at $z < 1$. At present both statistical and systematic uncertainties in these measurements are large. A wide-area survey, such as might be used to measure weak lensing and perform a supernova search, would bring the statistical errors down to the level of a few percent at $z < 5$. This extra precision will become increasingly valuable in conjunction with complementary information from QSO absorption lines and from studies of high-redshift galaxies with the Space Infrared Telescope Facility (SIRTF), JWST, and the Atacama Large Millimeter Array (ALMA).

3.2.2. *Galactic Evolution*

HST probes galaxy evolution both through deep observations of distant galaxies and through detailed studies of nearby galaxies. For distant galaxies, HST observations yield detections beyond groundbased limits, photometric redshifts and Lyman-break selection in redshift ranges unaccessible from the ground (e.g. $1.3 < z < 2.5$ and $4 < z < 13$), and measurements of sizes and morphologies. The areas covered by HST so far are only just now becoming large enough to be interesting for studies of clustering, environment, and large-scale structure. Such clustering studies are essential to make the connection between galaxies and dark-matter halos, and through this connection provide critical tests of how star and galaxy formation proceeds in the early universe. Because direct measurements of galaxy kinematics in these compact, and often distorted, galaxies are difficult to interpret, **measurements of the bias parameter b as a function of galaxy properties (e.g. star-formation rates, stellar masses and morphology) may be the best way to constrain parameters of hierarchical models of galaxy evolution.** While shallow surveys that are compatible with supernova searches and lensing are adequate at $z < 3$, detecting a sufficiently high density of galaxies at higher redshifts requires much longer exposures. Even if 500 orbits per cycle ($\sim 15\%$ of the observing time) were devoted to deep imaging, HST would cover only 0.25 square degrees to Hubble-Deep Field depth in four filters prior to 2010. Serious studies of large-scale structure will require either larger investment of observing time (at the expense of other projects) or a wide-field imager.

Current observations have just begun to tap the HST potential for slitless spectroscopy. The ACS grism, and the WFC3 grisms after SM4, provide a unique low-resolution spectroscopic capability in a region of the sky dominated by terrestrial emissions from the ground. Such observations are likely to be the most effective way to find Lyα emission-line galaxies at $z > 5$. Obtaining interestingly large samples for measurements of clustering and detailed comparison to other populations of high$-z$ galaxies will require several thousand orbits.

Ironically, studies of very nearby galaxies are just as difficult as deep surveys. Indeed the deepest HST observation to date is on a field centered on the M31 halo (Brown et al. 2003). These observations yielded the surprising result that 30-50% of the stellar mass in this field was formed less than 8 billion years ago, significantly later than the formation epoch, ~ 12 Gyr ago, inferred for Milky Way halo from globular cluster and field-star studies. So far this field is the only main-sequence turnoff (MSTO) that has been measured beyond the environs of the Milky-Way and its satellites. It will be important to extend this work to other portions of the M31 halo as well as other galaxies. Observations of the main-sequence turnoff are feasible with HST for every galaxy in the Local Group, but it would take an investment of several thousand orbits to do this. **Nevertheless, such color-magnitude diagrams would answer the question whether galaxies generally began forming at the same time, or whether some started forming stars later than others.** This is a particularly interesting question for relatively isolated dwarf galaxies, which may have experienced a delay or hiatus in star-formation due to ionization of their ISM by the UV background.

For galaxies outside the Local Group, direct observations of the MSTO are infeasible, but indirect constraints on star-formation histories can be derived from color-magnitude diagrams of the horizontal branch and giant branch, as well as from surface-brightness fluctuations.

3.2.3. *Stellar and Planetary Origin and Evolution*

HST has contributed greatly to our understanding of stars and stellar evolution. Studies of star-forming regions, protostars, protoplanetary disks, and Herbig-Haro objects have illuminated stellar births. Star-cluster studies have provided important constraints on stellar evolution (for example, forcing a re-examination of models for the core-helium burning phase of stellar evolution). Studies of planetary nebulae, neutron stars, white dwarfs, supernovae, novae, and their remnants have greatly increased our understanding of the very late stages of stellar evolution and stellar deaths. As for many topics, progress is limited by observing time availability, not technology or lack of sources to study.

The physics of star formation: stellar nurseries

Approximately 80% of Galactic stars form in clusters like the Orion Nebula. High resolution UV and optical data are vital to understanding the various feedback processes involved in star formation. HST observations map energy transport through shocks and photoionisation, probe the detailed structure of accretion disks and associated jets and outflows, and trace variations in the morphology of protoplanetary disks (Bally et al. 2000; O'Dell 2001). The subsequent evolution of gaseous disks can be traced through high spatial-resolution ultraviolet and visual spectroscopy (Roberge et al. 2002, 2001). To date, only a very small portion of the area of nearby star-forming regions have been observed by HST, at a limited number of wavelengths. A comprehensive multiwavelength study of the Orion nebula would yield order-of-magnitude advances in our understanding of the demographics of young stars, protoplanetary systems, and feedback processes with the surrounding environment. Such a study would take more than a month of telescope time. An extensive program of such observations will be particularly powerful when coupled with JWST mid-infrared spectroscopy and photometry, which probes the dust content in those systems.

Extrasolar planets and their atmospheres

HST has also proven to be a particularly powerful tool for studying extrasolar giant planets. The high photometric precision allows accurate determination of their physical properties (Brown et al. 2001), while HST spectroscopy provides the only means of studying their atmospheres (Charbonneau et al. 2002). Even prior to 2010, we may expect HST to contribute significantly to finding planets through transits, microlensing, astrometry and perhaps direct imaging.

Radial velocity searches have rather robustly shown that 0.5-0.7% of solar neighborhood stars have planets with $P_{\rm orbit}$ below 5 days (the set referred to as "Hot Jupiters"). In principle, detection of 5 such transiting planets requires monitoring 10,000 stars. This is being very actively pursued with wide-angle small telescopes (see Horne 2003 for a review). **By 2010 we can expect groundbased radial-velocity and transit surveys to reveal 5-10 stars for which transit-spectroscopy is possible with HST.** Spectroscopy of the transits with HST can be used to search for carbon monixide, water, sodium, and other features. HST's short-wavelength spectral coverage is complementary to JWST here, and HST will be the only facility with the sensitivity and photometric stability for such measurements between 2010 and the launch of JWST.

The addition of an optimized coronagraph to HST would open major new vistas, allowing detection and spectroscopy of earth twins around the nearest stars, planets like Uranus and Neptune on Mars/Jupiter-like orbits around stars to 5 pc, as well as planets like Jupiter and Saturn to 10 pc (see Fall et al. 2003 for details).

3.3. *Emerging Observational Techniques*

Much of the recent dramatic progress in astronomy has been fueled by advances in technology and in observational techniques. A number of these emerging techniques rely on high resolution and stable photometry; HST in the early part of the next decade is likely still to have the best general capabilities in these areas. The following are among the most exciting new developments of relevance to HST.

Microlensing. HST time-series observations of fields in or projected on the Galactic bulge provide important constraints on the stellar and sub-stellar mass function. HST observations can measure the microlens parallax to set interesting constraints on micro-lens masses and locations for long-duration events. HST is in many cases the best facility for setting constraints on the optical brightness of the lenses.

Transits. HST's stable point-spread function makes it an excellent facility for searching for planetary transits via time-series data with millimagnitude precision. HST is just beginning to apply this technique to set constraints on planetary frequency in different environments (Gilliland et al. 2000). Spectroscopy during transits offers a unique probe of the atmospheres of extrasolar planets.

Coronagraphy. HST coronagraphic observations have provided access to unexplored regions near bright sources, such as stars and AGN, which have been heretofore obscured by scattered light. Spectral deconvolution techniques that are beginning to be applied with HST can reach the Poisson-noise limit for coronagraphic imaging and low-resolution spectral applications (Sparks & Ford 2002; Sparks et al. 2002). Recent developments in coronagraphic hardware (deformable mirrors and advanced pupil masks) also have shown tremendous progress (Kasdin et al. 2003). While much can be done with existing instruments, an optimized coronagraph for HST would be an extremely effective way to advance our knowledge of extrasolar planets and planet formation.

Weak Lensing. Statistical measurements of galaxy shapes have emerged as an important tool for measuring dark matter and constraining dark energy.

As analysis techniques improve, this will be a key area for HST. A wide field imager is a promising addition to HST that could open up a wealth of applications in this area.

4. DISCOVERY SPACE: ANTICIPATING THE UNANTICIPATED

Many of HST's greatest contributions have come in areas that were unexpected at the time of launch. For example, at the time of launch HST was not expected to provide major advantages in detecting distant galaxies (Bahcall et al. 1990). But distant galaxies turned out to be smaller than expected and HST's detection advantages relative to ground-based facilities have proven to be extremely important. Indeed, as measured by papers, citations, and proposal pressure, studies of distant galaxies have proven as significant to HST science as measurement of the Hubble Constant or studies of QSO absorption lines.

The benefit of having a multi-purpose space observatory — as opposed to a mission specifically tailored to just a few science goals — has been demonstrated repeatedly with HST. A few examples:

- HST Observations of the comet Shoemaker-Levy impact with Jupiter have contributed enormously to both the public and scientific understanding of comet collisions and planetary atmospheres.
- The use of SNe Ia as cosmological standard candles was regarded as somewhat speculative at the time of HST launch. Eight years later, HST provided the precise photometry of high-z supernovae that was essential for the discovery of cosmic acceleration. More recently, HST has been effective finding and monitoring supernovae at $z > 1.3$, where groundbased confirmation of the expected deceleration has proven to be extremely difficult.
- HST observations of Gamma-Ray burst sources helped to identify the objects as cosmological, demonstrated that they were associated with galaxies (but not the centers of galaxies), and provided both early-epoch UV and late-epoch optical photometry of the transients that has been critical for elucidating the detailed physics of these sources.
- HST made the first detection of the atmosphere of an extrasolar planet using precise time-series spectroscopic measurements not conceived of by the builders of HST or the spectrograph.

The pace of astronomy is such that it is difficult to predict several years in advance which new phenomena or observations will be of greatest importance. Nevertheless as outlined in §5, HST high-resolution optical and UV capabilities are likely to remain unique until well into the next decade. Were HST to be decommissioned sooner we would likely miss out on the opportunity to followup new sources detected at other wavelengths or via other techniques (e.g. from ALMA, JWST, LIGO, etc.) or carry out detailed studies of remarkable transient events (nearby supernovae, comets, microlensing events, gamma-ray bursts, etc.).

5. FACILITIES WITH OVERLAPPING CAPABILITIES

HST has proven itself a powerful, versatile astronomical facility and remains at the forefront of current capabilities. In this section we consider NASA/ESA and groundbased facilities with overlapping capabilities.

5.1. *JWST.*

The James Webb Space Telescope is currently envisioned to cover wavelengths $\lambda = 0.6\mu$m to 28μm. JWST will supercede HST for most purposes longward of 1 μm. Capabilities at shorter wavelengths will be limited to wide-band imaging and very low-resolution ($R < 100$) spectroscopy. The observatory image quality requirements do not guarantee better performance than HST shortward of 1 μm. JWST is currently slated for launch in the middle of 2011. Significant technical, budget, and schedule challenges remain.

5.2. *SNAP.*

The Supernova Acceleration Probe is envisioned as a 2-m wide-field telescope with a 0.7 sq. degree FOV. Optical and NIR imagers would provide broad-band imaging with an image quality only slightly poorer than that of HST WFPC2 and NICMOS. A low-resolution spectrograph would provide redshifts for supernova candidates. Optimizing SNAP for supernovae necessarily entails compromises that will limit its effectiveness as a general-purpose observatory, even if the mission were to have a significant General Observer program. SNAP would *not* provide the following capabilities, now present on HST: (a) diffraction-limited imaging from 1200Å to 1.7μm — SNAP pixels will be $> 0.1''$ compared to $0.025 - 0.05$ on HST (b) imaging and spectroscopy shortward of 3500Å, and (c) high-resolution optical spectroscopy, such as used to measure kinematics in the centers of galaxies with HST. Nevertheless, SNAP would fulfill a critical need for a wide-field broad-band imager for cosmological studies. SNAP is envisioned as a joint NASA/DOE project, but is not currently funded as a project within NASA. If SNAP were selected as the first Einstein probe it would likely be launched no earlier than 2012.

5.3. *GALEX and FUSE*

As the only other NASA missions with UV capabilities, GALEX and FUSE have some overlap with HST. GALEX's domain is wide-field low-resolution $3-5''$ imaging and grism spectroscopy, which has very little overlap with HST high-resolution high-sensitivity UV imaging and spectroscopy. FUSE carries out high-resolution spectroscopic observations shortward of the HST far-UV cutoff. Both missions are expected to end well before 2010.

5.4. *NHST*

A successor to HST at UV/Optical wavelengths was considered important in the last NAS decadal survey (McKee et al. 2003), but planning for such a mission is in its early phases and launch would not occur before ~ 2020 in current NASA plans. A recent review of the relevant science and technology is presented by Sembach et al. (2003).

5.5. *8-10 m class telescopes.*

Large groundbased telescopes now generally surpass HST sensitivity for $0.35 < \lambda < 1\mu$m spectroscopy at resolutions $R > 100$. HST is still far superior in optical imaging and has an edge in low-resolution spectroscopy at wavelengths longward of 0.8μm due to the more favorable sky background. While adaptive optics (AO) techniques are proving extremely effective in achieving observations close to the diffraction limit at near-infrared ($1-2.5\mu$m) wavelengths (Close 2003), current observations still generally require natural guide stars ($R < 14$ mag) within $10''$ of the target of interest. Laser guidestars will permit increased sky coverage.

AO at visual wavelengths ($\lambda < 1\mu$m), however, has proven much more difficult than anticipated at the time of the last decadal survey. The small diameter of the aplanatic patch at these wavelengths requires that actuator-operated mirrors correct for high harmonics to achieve even moderate improvement in a small (20 arcsecond) field of view. Current results are limited to low-Strehl ($< 20\%$) observations of binarity in bright ($V < 7$) stars. Imaging over arcminute scales and larger requires complex conjugate optics, and full development likely lies more than 15 years in the future. **Space-based platforms are likely to remain the optimum choice for high resolution visual ($< 1\mu$m) photometric or spectroscopic programs (Close 2003) well into the next decade. UV observations will always required space observatories.**

5.6. *Giant Ground-Based Telescopes*

The Giant Segmented Mirror Telescope, or its equivalent (e.g. CELT) is envisioned as a 30-m optical-IR groundbased facility. Current plans call for diffraction-limited imaging using laser guide stars longward of 0.85μm. Images would be seeing-limited at shorter wavelengths, and thus still not generally competitive with HST in depth or resolution. CELT first light is expected to be no earlier than 2013 and cost is estimated at roughly $\$700M$.

The following are general conclusions from this comparison. (1) HST capabilities for sensitive high-resolution optical/UV imaging and spectroscopy are unlikely to be replaced or superceded by any mission currently in the planning phase. (2) Major facilities with overlapping capabilities (JWST, SNAP, and CELT) will not be online by 2010 and are challenged to meet their goals of 2011 to 2013.

6. NEW INSTRUMENTS

The SM4 instruments will ensure that HST maintains its unique contributions—high resolution, low background, and uninterrupted wavelength coverage from 1200 nm through 1.7μm—throughout an extended lifetime. History shows that HST's scientific productivity will continue to increase even with a constant complement of instruments: the number of refereed WFPC2 papers per year continued to grow from its installation until it was superceded by ACS. History also shows that new instruments greatly enhance the scientific return of HST as well as its public visibility. As long as a cost-effective safe end to the HST mission can be found (e.g., by including a propulsion module as part of SM5), the incremental cost of new instruments is well below that of an Explorer mission, and the total impact of an end-of-life mission with new instruments on the NASA space science budget is comparable to a Discovery mission or Einstein Probe.

Previous instruments for HST have not shied from daring technological innovation, which has often brought great rewards: MAMA detectors enable large-format, high-sensitivity UV observations for STIS; cryocoolers allow the continued use of NICMOS with improved performance shortward of 1.8μm; and HgCdTe detectors with 1.7μm cutoff meet the challenge of making WFC3 an efficient IR imager within its limited mass, volume, and power budget.

Technological advances in the last few years offer the opportunity for similar advances over the existing instruments. The competition for instruments for SM4 brought forth nearly ten independent, innovative concepts, including various forms of multi-object spectrographs (which have spurred two of JWST's instruments), energy-sensitive imagers, and high-performance coronagraphs. Similarly, two of the concepts offered to date for SM5—wide field imaging and high performance coronagraphy—would probe new ground for HST. Such new instruments might require require active optics and creative solutions to fit within the volume and power envelope of HST, as well as to handle increased data volume. Such technical challenges are the norm in instrument development, and are not unlike those faced by a stand-alone missions (e.g., an Einstein Probe or Discovery mission) with the same observational requirements; in fact, such instruments would validate the technology for other NASA missions requiring wide-field imaging or high-contrast coronagraphy on a well-characterized platform such as HST.

Selection of new instruments should tap the reservoir of technologically innovative ideas in the astronomical community. NASA has an enviable track record in ensuring the selection of technically feasible instruments which will greatly augment the scientific capability of HST. With a possible mission *circa* 2009, there is enough time for new ideas to be developed competitively, with focused maturation of selected technologies that are of strategic interest to the space science program. Here we mention briefly three such ideas, fully expecting that many other innovative ideas could be suggested in response to an Announcement of Opportunity.

6.1. *Wide-Field Imager*

It is technically possible to construct a wide-field imager for HST with a field of view $\sim$ 10 times that of ACS. A relatively simple design is a replacement for one of the Fine Guidance Sensors, with a field of view somewhat larger than the FGS pickle. The pointing functions of the replaced FGS can be achieved by internal guiding arrays, for which the necessary interfaces already exist in the FGS bay. (Options other than replacing FGS are possible; for example high multiplexing capability for surveys could be achieved through the use of dichroics to allow simultaneous imaging of the same field of view using different detectors at different wavelengths.) Smearing of the PSF due to differential velocity aberration is not a significant problem for most applications. Current HST weak-lensing measurements, for example, experience the aberration at similar or larger levels due to the use of parallel data (Refregier et al. 2002). Were a new camera to include an infrared channel, the IR detectors would be nearly identical to those in WFC3. With the Wide Field Imager, HST could cover $\sim$ 30 square degrees per year in multiple bands to $I \sim 26$; combined with aggressive scheduling techniques and improved data handling, areas as large as 1000 square degrees could be observed in four years to a limiting magnitude $I \sim 25$.

6.2. *A High Performance Coronagraph*

A high-performance coronagraph, similar to that proposed for SM4, would allow detection and spectroscopy of planets like Uranus and Neptune on Mars/Jupiter-like orbits around stars to 5 pc and of planets like Jupiter and Saturn to 10 pc (see Fall et al. 2003 for details). It would also enable observations of circumstellar disks closer to the parent star and around more distant stars, and perhaps earth twins around the nearest stars. This instrument requires an optical device to compensate for wavefront errors in the HST primary and secondary. The best wavefront correction can be achieved using a deformable mirror configured in orbit after installation and subsequently adjusted only rarely if ever. Thermal variations in the telescope assembly could be controlled with active tip-tilt-focus control. Even a static mirror microfigured to compensate for the known figure errors of the HST optics would be sufficient to achieve many of the science goals. Spectral deconvolution (Sparks & Ford 2003) can help control systematics such as breathing. While such an instrument would be technically innovative relative to existing HST instruments, existing designs and laboratory-demonstration hardware show its feasibility. The on-orbit characteristics of HST optics are well calibrated and further on-orbit measurements are of course possible if required to optimize the instrument design.

6.3. *Integral Field Spectrograph*

Integral Field Spectrographs based on image slicing are now in active use on the ground, and one is planned for the Mid-Infrared Instrument for JWST. This instrument may be technologically less challenging than others, and opens up the possibility of full spectroscopic mapping of core regions of galaxies, AGN, and star-forming regions. With an Integral Field Spectrograph, HST could survey a complete sample of nearby galaxies of all morphological types, measure their central kinematics and the mass of the central black holes, and relate their properties with nuclear activity and nuclear star formation.

6.4. *Other concepts*

Other instrument concepts include a higher-throughput two-dimensional spectrograph — taking advantage of the significant quantum-efficiency advances for UV photocathodes over the past several years — a low-resolution multiobject spectrograph either in the UV or the NIR, or a UV-optical instrument with an energy-resolving Transition Edge Sensor (TES) or Superconducting Tunnel Junction (STJ) detector used either an imager or as a spectroscopic order-sorter (Romani et al. 2003).

7. HST AND JWST

Careful planning is required to provide the critical short-wavelength coverage necessary to maximize the science return from JWST. If experience is a guide, anticipating the most important programs of an observatory more than a few years in advance is extremely difficult. The closer the two missions are to being contemporaneous the greater the likelihood that supporting HST observations will be relevant to the highest-priority JWST observations. Deep HST observations are particularly important as a way of identifying galaxies at $z < 5$ via the Lyman-α spectral discontinuity. While interesting in their own right, such lower-redshift objects will be an important source of confusion for JWST in its quest for the earliest galaxies at $z > 7$. Having the two missions overlap in time would open possibilities for simultaneous observations of supernovae and other cosmological transients (for which data at $\lambda < 0.6\mu$m may be very valuable), microlensing events (for which the separation of the two spacecraft will sometimes provide measurable photometric and astrometric parallaxes), and transient phenomena in our solar system and other planetary systems.

Space missions continuously evolve, sometimes dramatically, from the time they are conceived, through their development phase and even during construction. The unique serviceability of HST can be used to science's advantage by optimizing the degree of complementarity with JWST, particularly if, because of schedule necessity, JWST is launched after 2013 or if its capabilities migrate even further into the IR region of the spectrum. Were instrument proposals to be solicited, the astronomical community would undoubtedly respond with an array of concepts that would strategically complement those of JWST.

7.1. *HST End-of-Mission Criteria*

While the HST mission could end at any time due to some unforeseen failure, *planning* an end to the mission is a considerable challenge. Important criteria include (a) when its capabilities are superceded by other facilities, (b) when the scientific questions it is capable of addressing are no longer considered interesting or important (by scientists and the general public). HST will still be a unique and valuable scientific resource in 2010, addressing some of the key questions likely to be facing astronomy.

8. SUMMARY AND CONCLUSIONS

The HST-JWST transition plan will determine the shape of astronomy in the early part of the next decade. A decision not to service HST after 2005 risks losing HST's unique optical-UV capabilities significantly earlier than JWST launch, and perhaps more than 10 years earlier than any comparable replacement facility. Servicing the telescope in ~ 2009 would greatly increase the chances of survival into the JWST era and would provide time to accomplish many of the ambitious science programs outlined in this document. Adding instruments to HST in this mission would strategically complement JWST and would provide a valuable early opportunity make headway on some of the key science goals in the NASA Origins and SEU programs, including measuring the effects of dark energy, finding black holes, and discovering and studying extrasolar planets.

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