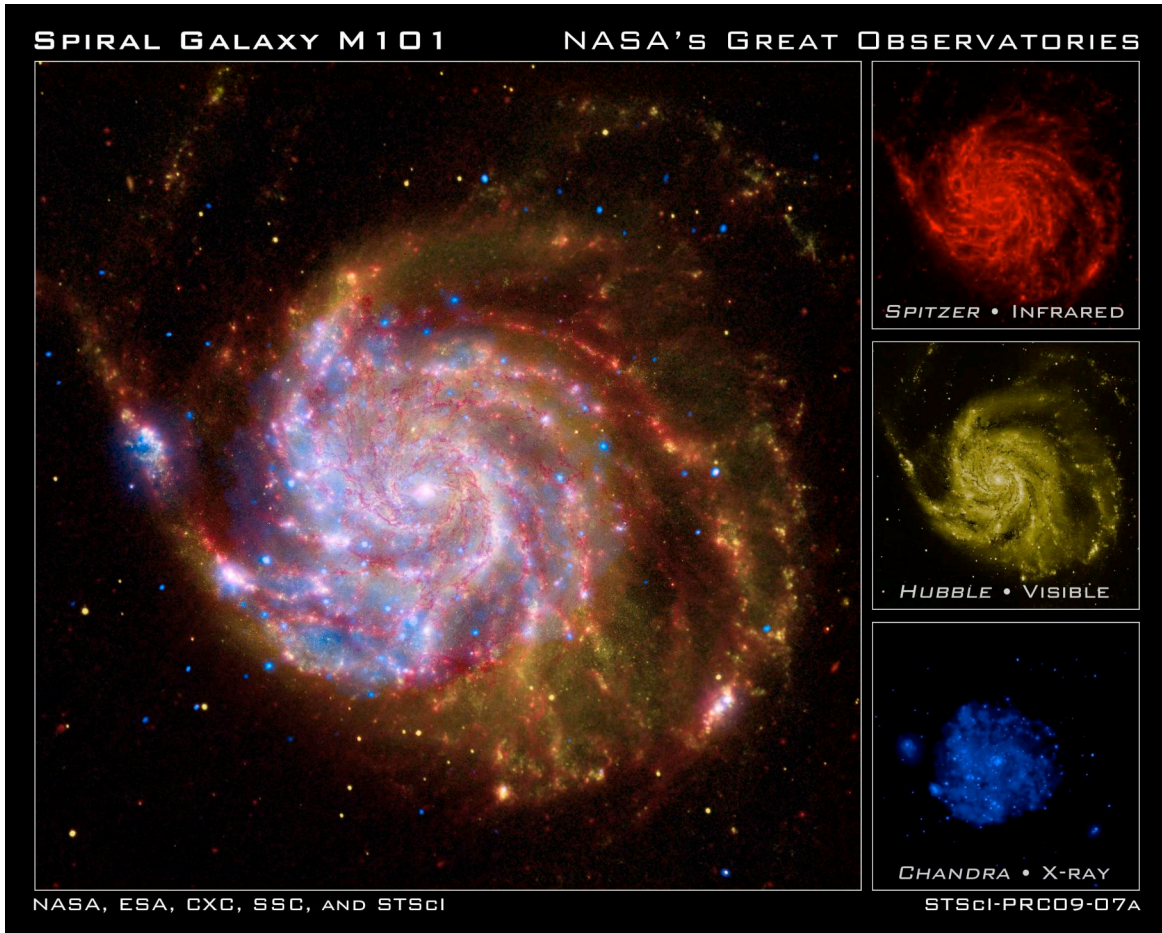


Astro2010
State of the Profession Position Paper
The Value of Observatory-Class Missions



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Introduction

The dramatic success of NASA's astrophysics science program over the past 20 years has resulted from a series of assets in space ranging from Small Explorers to Observatory-Class missions. NASA's Observatory-Class missions, such as the Chandra X-ray Observatory (CXO), the Hubble Space Telescope (HST), and the Spitzer Space Telescope (SST), form the cornerstone of this program by providing all researchers, regardless of institutional affiliation, a spectrum of science opportunities across programs large and small. These observatories stand out in their breadth of capabilities and consequent diversity of high impact science, their reach within the scientific community, and their proven ability to inspire the nation. Each mission was designed to address specific scientific imperatives recognized by past Decadal Survey Committees, whether it was to refine the extragalactic distance scale, examine galaxies as they were in the distant past, determine the relationship between black holes and quasars, observe the ultimate fate of stars in their death throes, or reveal heavily obscured regions of star-formation. These were ambitious goals, as are those envisioned for future Observatory-Class missions, such as the James Webb Space Telescope (JWST).

Chandra, Hubble, and Spitzer have suites of instruments with capabilities – high sensitivity, diffraction-limited imaging, spatially-resolved spectroscopy, superior angular resolution, stable point spread functions – far exceeding those of previous missions. By virtue of their operation as general-purpose observatories committed to returning the highest quality science possible, there are few areas of astrophysics that have not been profoundly affected by these facilities. Their continuing contributions to science, the astrophysics community, and the nation remain strong after nearly 33 years of combined service. *With this white paper, we urge the Astro2010 Committee to reflect upon the role that these missions have had in shaping astrophysics in the past decade, and to consider the value of making investments in the next decade to enable cost-effective Observatory-Class missions in the future.*

Observatory-Class Mission Value to Science

Observatory-Class Missions form the core of NASA astrophysics research and support a great diversity of science programs:

- **Chandra** has probed the geometry of space-time around black holes, unveiled the role of accreting supermassive black holes in influencing the evolution of the most massive galaxies, demonstrated that dark matter must exist, and provided independent confirmation of the existence of dark energy. Chandra has also tracked the dispersal of heavy elements by supernovae and measured the flaring rates of young Sun-like stars with implications for the formation of planets.
- **Hubble** has mapped the expansion rate of the Universe and provided proof that it is expanding under the influence of dark energy, given us our deepest views of the cosmos, probed galaxy evolution at high redshift, established that galaxies have massive black holes at their centers, and detected the cosmic web of intergalactic material in the low-redshift Universe. Nearer to home, Hubble has imaged protoplanetary disks, provided new insights into planetary phenomena ranging from the variability of Jupiter's Great Red Spot to the discovery of two additional moons of Pluto, and measured the composition of extrasolar planet atmospheres.

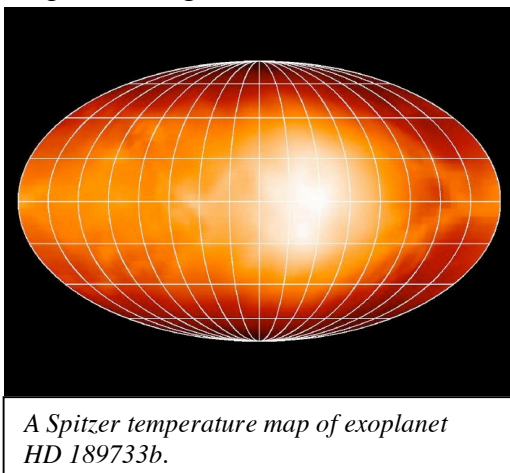
- **Spitzer** has characterized the physical properties of exoplanets, demonstrated that mature galaxies exist at $z > 6$, resolved the far-infrared background into individual point sources, and identified clusters at $z > 1$. Spitzer has discovered spatial variations in the dust composition of the Cas A supernova remnant, provided a better understanding of the building of planetesimals in circumstellar disks of young stellar objects, and shown that the mineralogy of Solar System comets resembles that of exozodiacal debris disks around nearby stars.

Thousands of different investigations have been performed over the years with NASA’s Observatory-Class missions, all selected on their science merit. Observing programs range from small investigations focused on single astronomical objects to comprehensive investigations that include many objects or perform substantial surveys. Some programs with very specific science goals require as little as an hour of observing time, while other programs designed to push the observatories to their detection thresholds may require several weeks of observing time to complete. It is impossible to do justice to all these programs here, but lists of approved programs can be found on the website of each observatory.

A simple, striking measure of the productivity of the three observatories is the number of refereed science papers they have produced. In a recent three-year period, more than 4600 refereed papers using data from Chandra, Hubble, or Spitzer were published – an average of ~30 papers per week. These papers account for approximately 20% of all papers, and 27% of citations to all papers (~84,000 of 312,000 citations), published in the primary U.S. and European astronomy journals in the same time period. The rate of publication continues to increase with time. Through the end of 2008, data from these missions had resulted in more than 12,800 refereed science papers, along with a myriad of review articles and papers in conference proceedings.

	Y2005	Y2006	Y2007	Sum
Chandra	509	550	489	1548
Hubble	675	688	723	2086
Spitzer	158	344	503	1005
Sum	1342	1582	1715	4639

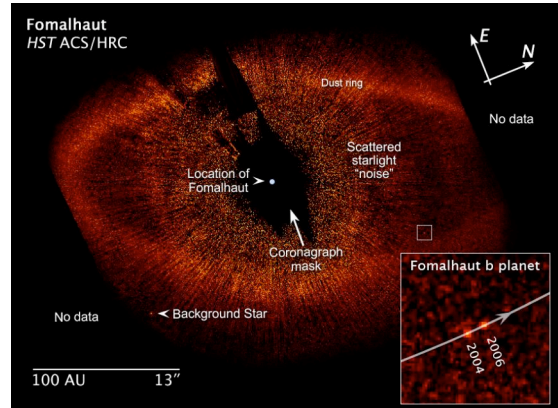
Breadth of capability provides Observatory-Class missions with flexibility to respond to scientific imperatives of the time and to pursue research that their designers hadn’t considered. Exoplanet research is an obvious and extremely important example. While the study of exoplanets began well after the scientific objectives of Hubble and Spitzer were defined, the



superb sensitivity and stability of both observatories have made them key platforms for characterizing exoplanets. Spitzer has determined temperatures and placed constraints on the chemical composition and atmospheric structure of exoplanets. Data obtained for HD 189733b dramatically illustrate this point. The figure at the left (Knutson et al. 2007) shows the temperature map of HD 189733b at 8 microns made from a 33-hour observation of the planetary transit. Data such as these are used to characterize heat transport within the planet’s atmosphere and the resulting distribution of temperatures around the planet. Hubble has detected methane in the

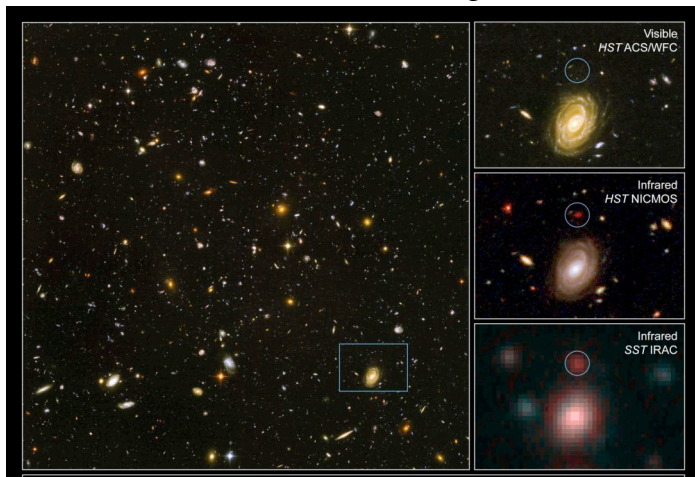
atmosphere of this same planet (Swain et al. 2008), and hydrogen, oxygen, and sodium in the

atmosphere of HD 209458b (Charbonneau et al. 2002; Vidal-Madjar et al. 2003, 2004). Hubble's superb imaging has also led to a direct image of an exosolar planet - Fomalhaut b (Kalas et al. 2008 – see adjoining figure). Exoplanets are now a major area of astronomical research with both observatories; in the upcoming cycle of approved Hubble proposals (post-SM4), exoplanet research will be conducted with 5 of Hubble's 6 science instruments, while more than 20% of the Spitzer Cycle 6 Exploration Science program will be devoted to exoplanet studies. By enabling multiple approaches to this field of study, Spitzer and Hubble are paving the way for exoplanet observations with JWST and future observatories.



NASA's Observatory-Class missions enable revolutionary changes in astrophysics by opening new fields of investigation and providing innovative ways to explore the Universe. Consider the study of deep extragalactic fields, which became a major area of astronomical research through the impact of the Hubble Deep Field project that was initiated in 1995. The success of this effort and the wealth of resulting science led directly to the Hubble Ultra Deep Field, the Chandra Deep Fields, and the Great Observatories Origins Deep Survey (GOODS; Dickinson et al. 2004; Giavalisco et al. 2004), which combined data from Hubble, Chandra, and Spitzer with the most powerful ground-based facilities to survey the distant Universe to the faintest flux limits across a broad range of wavelengths. The deep fields have become standard regions of sky used to study the cosmic histories of star formation, chemical evolution, the mass assembly history of galaxies, the morphological evolution of galaxies, reionization of the Universe, properties of AGNs, gravitational lensing, cosmic variance, and a host of other important astrophysical phenomena.

By combining multi-wavelength observations, GOODS has led to numerous discoveries that would otherwise not have been possible. For example, the discovery of massive red galaxies at high redshift resulted from the combination of Hubble and Spitzer GOODS data.

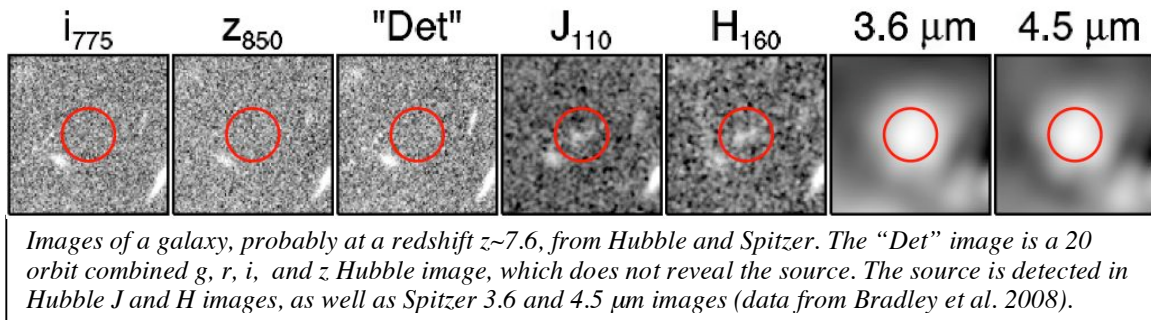


The accompanying press release photo (STScI 2005-28) shows an example of one such galaxy at $z > 6$. Similarly, the combination of Chandra and Hubble has permitted the study of obscured active nuclei and the discovery of galaxies with extreme X-ray to optical flux ratios. The Chandra Deep Fields find the highest AGN space density to date (2900/sq. deg; Bauer et al. 2004) and, in combination with Spitzer for

both deep and moderate depth surveys, offer the most complete view of the AGN population, including elusive obscured AGN.

With the Deep Fields as a proving ground, similar techniques for studying the distant Universe are being applied to other fields (e.g., COSMOS, AEGIS, etc.). The power of Spitzer

and Hubble have propelled to the fore the study of the earliest stages of galaxy formation, when the Universe was less than 1 billion years old. Using deep observations from these observatories

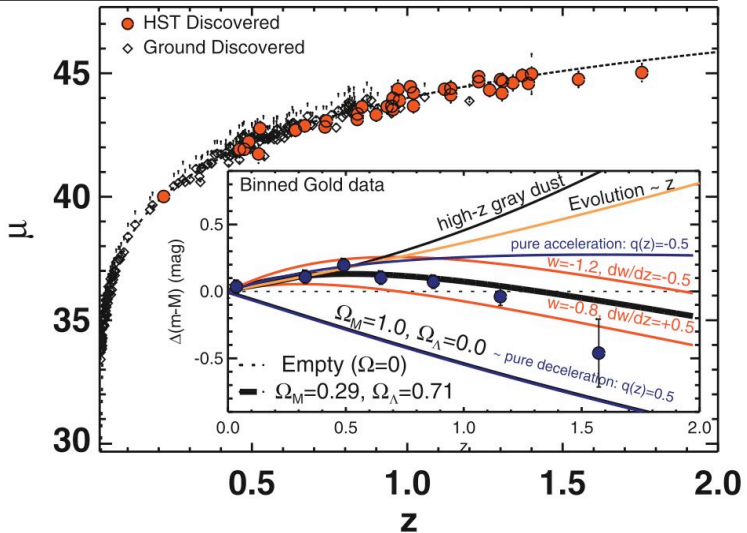


and the gravitational lensing power of clusters of galaxies, researchers have discovered galaxies at redshifts of 5 and beyond. The technique of finding such galaxies by their strong Lyman breaks and Balmer decrements has been employed to identify high redshift objects and to determine masses, ages and star formation rates in the most distant galaxies ever detected. This is illustrated in the figure above, which shows images of a candidate galaxy at $z > 7$.

Observatory-Class missions provide momentum and sustainable impact to burgeoning fields. They have the power and longevity necessary to make an immediate impact on new discoveries and then continue to propel developing fields forward over many years. For example, in 1998 two teams of astronomers announced the surprising result that the expansion rate of the Universe is accelerating, propelled by a mysterious dark energy (Riess et al. 1998; Perlmutter et al. 1999). The results were derived from observations of nearby and distant type Ia supernovae and their utility in measuring changes in the cosmic expansion rate. Ground-based

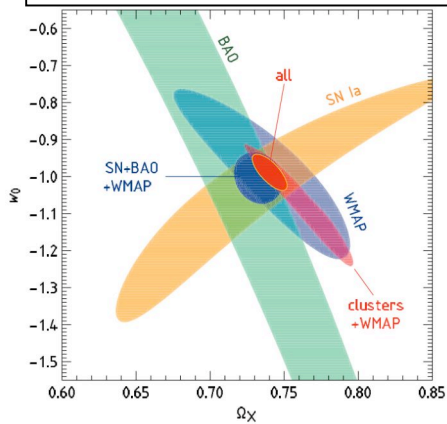
telescopes provided the majority of the data, but Hubble provided some of the most precise measurements of the recent growth history that revealed the accelerated growth rate. From 2002-2005, Hubble found 25 of the most distant SNe known, all at $z > 1$, culminating in the first highly significant detection of the preceding, decelerating epoch of the Universe and confirming the reality of cosmic acceleration (see figure at right; Riess et al. 2007). More recently, Hubble has been used to derive a new measurement of H_0 with improved precision by using a differential distance ladder. The resulting 4.8% precision in H_0 coupled with the WMAP value of $\Omega_M h^2$ results in a dark energy equation of state parameter, $w = -1.12 \pm 0.12$, competitive with the best measurements of w today (Riess et al. 2009).

SN Ia Hubble diagram demonstrating that the expansion of the Universe is accelerating.



Although the existence of dark energy was unanticipated when Chandra was designed, its capabilities have also allowed astronomers to develop methods to assess the properties of dark energy. Clusters of galaxies are the most massive collapsed objects in the Universe and their

Dark energy constraints in a flat Universe from a combination of all datasets.

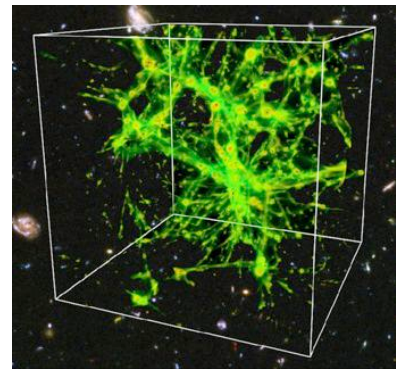


growth depends critically on the properties and parameters of the Universe itself. One technique relies on using Chandra to determine how the number of massive clusters per unit volume changes with time, which depends on the competition between gravity and the accelerated expansion caused by dark energy. Comparison of the growth of linear density perturbations derived from X-ray cluster mass functions with the predictions of cosmological models demonstrates the need for a non-zero cosmological constant and constrains the dark energy equation of state to $w = -0.991 \pm 0.045(\text{stat}) \pm 0.039(\text{sys})$ when combined with cosmic microwave background, supernovae, and baryonic acoustic oscillations results (Vikhlinin et al. 2009, see figure).

Observatory-Class missions offer longer-term opportunities to follow and contribute to fields of study as they mature. The resulting science momentum helps to direct efforts and make progress on difficult problems. This is valuable for fields that have a long history but still have much to reveal (e.g., star formation, galactic structure, stellar populations, galaxy evolution, the intracluster medium, the intergalactic medium), as well as nascent fields for which we are only beginning to obtain observational data (e.g., dark matter and dark energy). Consider, for example, the development of large-scale structure and the evolution of the cosmic web of matter. While it is possible to trace the gravitational peaks in the structure distribution through galaxy redshift surveys from the ground, the gaseous component of the cosmic web in the modern Universe ($z < 1$) is observable only from space and remains relatively unexplored. In recent years, the cosmic web gas has been recognized as a significant baryon repository. As the importance of using the cosmic web to test cosmological simulations has grown, so too has interest in observing the intergalactic gas with Hubble and Chandra (Nicastro et al. 2005; Tripp et al. 2008; Oppenheimer & Davé 2008).

Similarly, the power of the observatories has been brought to bear on dark matter. A deep Chandra observation of 1E0657-56 (the “Bullet Cluster”), a merging system with a unique, clear-cut geometry, was combined with deep optical data from Hubble and ground-based telescopes to investigate the distribution of dark matter. The observed separation between the dark matter sub-cluster, whose matter distribution was derived using gravitational lensing, and the Chandra-measured distribution of hot cluster gas – the dominant baryonic-matter component in the cluster – provides the most compelling evidence yet for the existence of dark matter. This finding removed the main motivation for alternative gravity hypotheses designed to avoid the need for dark matter (Clowe et al. 2006).

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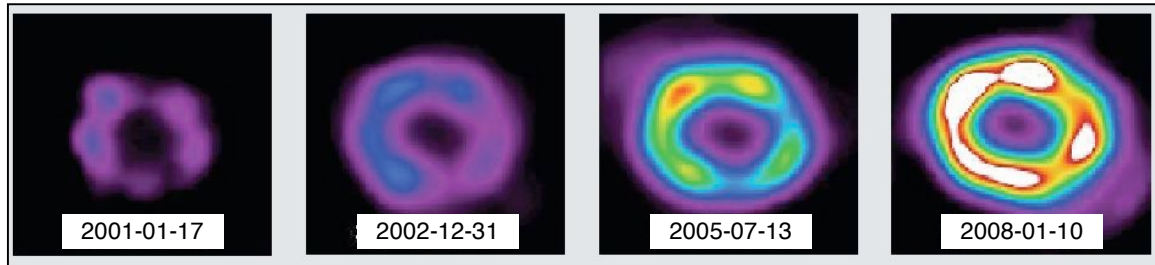


A simulation of the cosmic web (Cen & Ostriker 1999) shown superimposed on a portion of the Hubble UDF.



The Bullet Cluster (NASA Press Release 06-297) showing X-ray data from Chandra (pink) and optical data from HST and ground-based telescopes.

Availability of Observatory-Class missions increases the chances that new discoveries can be followed-up in a timely manner and offers multiple instrument options for urgent investigations. The combination of general-purpose capabilities and longevity make it possible to capitalize on unique targets of opportunity (e.g., the Shoemaker-Levy 9 impact on Jupiter in 1994, the Deep Impact encounter with Comet Temple/1 in 2005, and the New Horizons Flyby of Jupiter in 2007), to follow the evolution of astronomical objects over many years (e.g, proper motions of binary systems, X-ray sources, and SNRs; changes in Solar System bodies), and to monitor or follow-up on transient phenomena (e.g., cataclysmic variables, supernovae, gamma ray bursts). For example, the evolution of a very young SNR (SN1987A) is being tracked for the first time by Hubble and Chandra. The figure below shows a ring of X-ray emission that continues to brighten as the blast wave encounters circumstellar material released from the progenitor star before it exploded.



Evolution of SN1987A X-ray emission and ring brightening as observed by Chandra.

The synergy of NASA’s Observatory-Class missions with each other, as well as with large ground-based optical and radio telescopes, is providing a more complete view of the astrophysical processes at work in shaping the past, present, and future of the Universe than has ever been possible. Multi-wavelength studies are now an integral part of the profession, and younger generations of astronomers have always had access to data from these observatories. Each observatory provides a unique perspective, and together the combined multi-wavelength result is often greater than the sum of the individual parts.



Multi-wavelength view of the Kelper SNR(left to right): X-ray – Chandra, Visible – Hubble, Infrared – Spitzer.

Observatory-Class Mission Value to the Profession

Observing time on Chandra, Hubble, and Spitzer is available to the worldwide community and is in high demand. These state-of-the-art observatories enable astronomers with the best scientific ideas to compete for observing time. Thousands of investigators from across the country and the

world participate in the proposal process each observing cycle. A summary of the proposal statistics for a recent 3-year period is given in Table 2.

	Proposals		Approved Proposal Size Range (hours)	Over-subscription		Time Available Per Cycle (hours)	Submitted Proposals (Cycle Averages)		
	Submit	Accept		Prop	Time		States	Countries	% Foreign PI
Chandra (Cycles 7-9)	2135	545	1.1 - 500	3.9	6.1	~4800	42	19	24
Hubble (Cycles 13-15)	1747	450	0.9 - 261	3.9	4.4	~3100	42	37	19
Spitzer (Cycles 2-4)	1873	596	0.4 - 511	3.1	3.9	~6000	35	26	21

Notes: Oversubscription rates for Hubble include only primary orbits, and do not include parallel or snapshot programs, which are also competed. HST time is awarded in orbits. A typical orbit duration is 53 min.

Observatory-Class missions provide critical research funding to the astronomical community. In recent years, Chandra, Hubble, and Spitzer observer grants have comprised 35-40% of all NASA astrophysics research grant funding. Most of these funds are used to support students and postdoctoral researchers who will become the next generation of leaders in the profession. Chandra alone has produced more than 100 PhD students worldwide. The observatory instrument development teams also receive direct science support in terms of guaranteed observing time and funding after launch (and servicing upgrades, in the case of Hubble). These GTO funds also support research staff, postdocs, and students. As an example, Spitzer has provided ~\$41M in direct GTO science funding since launch. In addition to funding researchers through their General Observer programs, the three observatories have sponsored named fellowships that are among the most prestigious in all of astronomy. In the 2005-2007 time period, 63 Chandra, Hubble, and Spitzer Fellows at 28 different US institutions received a total of ~\$16M in support. Those Fellows came from 35 different PhD-granting institutions worldwide.

	Cycles	Funding (\$)	Awards
Chandra	7-9	33M	528
Hubble	13-15	67M	1305
Spitzer	2-4	68M	1177
Sum		168M	3010

Table does not include GTO grants or fellowships.

Observatory-Class missions have data that are fully calibrated, easily accessible, and well-documented. One does not need to develop an insider's expert knowledge of the telescope and its instruments to conduct forefront research with these observatories. They provide assistance when needed, vetted software tools, and standardized data formats. The ease with which these data can be used has resulted in many publications that rely upon data from two or more of these missions. A simple query of the NASA/ADS abstract server yields more than 700 refereed publications that mention at least two of these missions by name in the publication abstract.

The Chandra, Hubble, and Spitzer data archives are recognized by the astronomical community as reliable, valuable sources of data. These missions have long enough time horizons to update calibrations requiring long time baselines to track (e.g., time-dependent sensitivity and flat-field changes, shifts in geometric distortion corrections) or that can be improved upon as

experience is gained. Tracking instrument performance over many years, identifying calibration deficiencies, and calibrating both routine and special observations to the accuracy desired by the astronomical community maximizes the quality of science returned as well as the quality of the archive produced. New techniques for analyzing data in these archives are also leading to new discoveries. For example, using new methods for optimizing reference point spread functions for images, Lafrenière et al. (2009) have recently shown that exoplanet HR 8799b is visible in archival Hubble data obtained in 1998, 10 years before its discovery image!

Archives are becoming more and more important in astronomical research as large datasets have been accumulated and it has become possible to retrieve, compare, and display data quickly. This is certainly true for NASA’s Observatory-Class missions. As an example, using the long time baseline

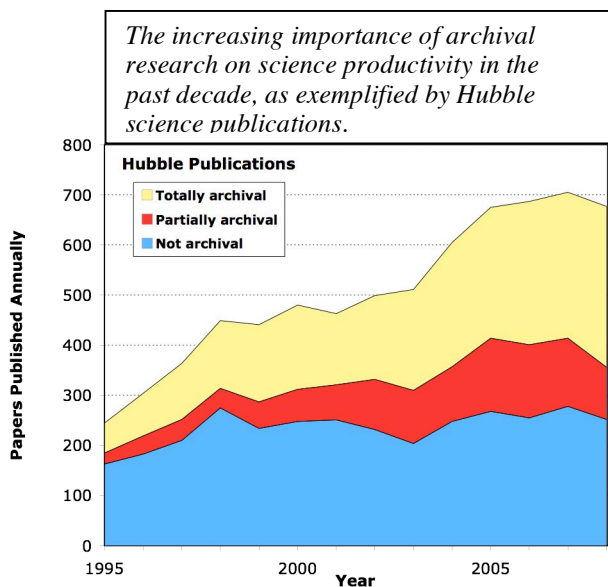
available for Hubble, we note that archival data now account for roughly half of all Hubble science publications. (See the State of the Profession white paper entitled “The High Impact of Astronomical Data Archives” by R.L. White et al. for further details.) This trend is likely to

	Total Size (Tb)	Total Size (Datasets)	Average (Y2005-2007)		
			Annual Ingest (Datasets)	Downloads per year	# Countries
Chandra	2.2	8035	912	~165K	~50
Hubble	35	602,000	~100,000	~1.2M	~70
Spitzer	15.8	20.2M	~4.8M	~40M	...

Includes raw and processed data, but not high-level science products.

continue into the foreseeable future, and we expect that similar trends will hold for future Observatory-Class missions as well.

An interesting characteristic of Observatory-Class missions is that they are large enough to address some big problems that in themselves become important projects. For example, Hubble required a good guide star catalog for the entire sky, which led to the Digitized Sky Survey (DSS) and the Guide Star Catalogs (GSC) 1 and 2. This was extremely challenging in the 1980s, but has paid great dividends. The GSC and DSS have become essential tools that are heavily used in the community across projects large and small. STScI currently distributes more than 10,000 DSS cutouts per day, and GSC is used by many space-based missions and ground-based observatories for target confirmation and guide star information.



Observatory-Class Mission Value to NASA and the Nation

Observatory-Class missions foster large, diverse user communities from small and large institutions spread across the United States and dozens of other countries. This means that the best minds can often be brought to bear on cutting-edge science problems, regardless of geographic location. Participation by U.S. and foreign investigators results in valuable collaborative connections to scientists in other countries. Roughly 20-25% of Chandra, Hubble, and Spitzer observing programs are led by foreign investigators. Funding for U.S. researchers is

spread across the country. The broad scientific participation that accompanies this financial support helps NASA and the science community reach and serve the entire nation, not just a few geographically isolated areas.

Observatory-Class missions play a crucial role in promoting and maintaining public awareness of science and NASA’s efforts to conduct science in space. The substantial breadth of science enabled by these missions yields a constant stream of science results that engage and inspire the public. Media coverage is frequent and widespread, reaching all areas of the country through newsprint, magazines, radio, television, and the internet. Consequently, the public has become so familiar with Chandra, Hubble, and Spitzer that these observatories are now synonymous with NASA’s science program. The American public recognizes the value of these missions and has high expectations for their scientific discoveries.

	Public Website	Public Website Pages /Month	# Press Releases	# Science-related Media Reports
Chandra	http://chandra.harvard.edu/	~1.3M	31	~800
Hubble	http://hubblesite.org	~20M	38	~2000
Spitzer	http://www.spitzer.caltech.edu	~5.5M	22	~500
<i>Media reports include only major news publications, magazines, and reports on the major television networks. Internet reporting is not included.</i>				

Table 5 lists some basic statistics for website usage and media coverage of the three observatories in 2008. In addition to the large amount of traffic (millions of web page views) to the science results and image releases on their award-winning web sites, the three observatories also attract significant visitor traffic to their on-line educational materials and serve millions of downloads of podcasts, on-line activities, videos, and digital images. The 2008 *Science News* metric, which measures NASA’s contributions to worldwide scientific discovery and technological achievement by assigning points for accomplishments reported in the news, lists Chandra, Hubble, and Spitzer among the top ten most productive space programs of the past 25 years. Hubble has been named as NASA’s most productive space mission in all but 3 of the 17 years for which the metric has been calculated. In 2007 Spitzer topped the list. Chandra and Hubble were included in Nature’s list of NASA’s top 10 achievements in its first 50 years. All three observatories appear in MSNBC’s recent (March 2009) list of “NASA’s Ten Greatest Science Missions”.

All three observatories have become an integral part of American culture. Astronomical images from the observatories can be found on record albums, book covers, iPhones, mouse pads, postage stamps, and art gallery walls. Stunning visualizations and other content from all three observatories are used in the programming of planetariums and science museums nationwide. Public familiarity with NASA missions maintains high levels of public awareness and support for NASA science research.

Observatory-Class missions have taken leadership roles in education and outreach activities, reaching directly into school curricula and textbooks to share the experience of exploration and discovery. They are inspiring and motivating students to pursue careers in science, technology, engineering, and mathematics. Training materials for K-12 students are distributed in every state. Hubble educational items are used in 40 of the 100 largest school districts. The Spitzer Teacher Research Program trains teachers to work closely with Spitzer scientists to make and publish Spitzer observations, and then to take advantage of that experience

in their teaching. Chandra materials have been incorporated into the test and study content for the astronomy competition of the National Science Olympiad, reaching both student participants and their teacher coaches in all 50 states from local to state to national levels. All three observatories have extensive web-based content devoted to enhancing the educational experience of the nation's youth and increasing knowledge of NASA-supported areas of science and nature.

Concluding Remarks

Observatory-class missions offer unparalleled power and versatility, with instrumental capabilities that give astronomers the opportunity to address a wide range of forefront scientific questions, including those that could not even be formulated when the missions were conceived. These observatories are accessible to, and used by, a substantial fraction of the worldwide astronomical community, and play a key role in developing the U.S. astronomical community through their support of research and researchers. The scientific results from these missions educate and stimulate the broader public, and inspire future generations of scientists. We ask that the Astro2010 Survey Committee take these considerations into account in developing an optimal strategy for U.S. astronomy in the next decade and beyond.

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