# Scientific Advancement through Flagship Space Missions

Astro2020 Decadal Survey State of the Profession White Paper on Fundamental Infrastructure

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**Key issue**: Large, strategic ("flagship") space missions provide unique value to advance the boundaries of science for multiple decades and to ensure US leadership in space and science. They offer advanced capabilities at the technological frontier, and they continually respond to new opportunities as the scientific landscape changes. These missions enable diverse science programs at all scales, and open, competitive access promotes and supports the most compelling research. Broad use of current strategic missions, often working together to enhance the observations' value, has produced high-impact and diverse results. Stable, systematic, and growing archives further enhance the scientific output, promoting repeated use of data sets for novel new investigations. Well-managed strategic missions maximize US science output and are well worth the investment they require.

## The Broad Role of Flagships

NASA develops space astrophysics missions at all scales, and this diversity supports broad and deep scientific advancement. Flagship missions are an essential component of this effective science portfolio, as the success of the Great Observatories demonstrates. Such missions are by definition large and strategic. They significantly exceed previous capabilities, and they provide broad utility rather than being focused as a specific experiment. The flagships most effectively advance "civilization-scale science" that asks the most fundamental questions. These strategic missions rewrite the textbooks, updating not only the facts but also the very subjects of interest.

The full range of science and scientists are most effectively supported with a combination of flagships and smaller-scale missions. The former engage a diverse and numerous user community, which cannot be equaled by dividing the resources across multiple smaller opportunities. More focused missions remain important—with specific strengths for example in concentrating on specific questions or being developed rapidly to respond to specific progress in the field—but the total successful portfolio requires the tall supporting pole of the large strategic missions that can address multiple questions and engage a growing community. The National Academies' 2017 study of NASA's Large Strategic Science Missions identified their multiple benefits, including being able to "answer many of the most compelling scientific questions."[1] Beyond the unique science they enable, flagships demonstrate the value of science to the citizens who fund these endeavors. Large strategic missions "produce tremendous science returns and are a foundation of the global reputation of NASA and the U.S. space program."[1]

## Past Discoveries and Continuing Innovation

Currently-operating NASA flagship astrophysics missions (Hubble, Chandra, and Spitzer) were conceived as a comprehensive program of Great Observatories, together (with Compton) providing a multiwavelength perspective to more fully account for the physical Universe (Figure 1). All three of these missions have produced high-impact science across the entire scope of astrophysics over their lifetimes since launch (in 1990, 1999,

Figure 1: Multi-wavelength observations of Messier 8 reveal the complexity of this star-forming region more completely. From left to right: Chandra, Hubble, and Spitzer each provide unique views, and the combination is essential to achieve a full understanding of star formation.

and 2003, respectively), and they remain extremely productive (Table 1). Their unique capabilities open new areas for research, and they flexibly respond as the scientific landscape alters.

One area where NASA's flagships have significantly advanced our understanding is of the formation and evolution of exoplanets. They provided the first direct measurement of an exoplanet's atmosphere[2] and the first atmospheric study of Earth-sized exoplanets[3]. Multiwavelength, sensitive data from Spitzer and Hubble reveal the role of clouds and hazes in diverse atmospheres (Figure 2)[4], and Chandra assesses the environment and likelihood of planet formation and survival[5]. A second major discovery area is the invisible Universe of dark matter, dark energy, and gravitational waves. Chandra observations of hot gas in clusters of galaxies are essential to map the dark matter that dominates their mass, which constrains its properties (Figure 3)[6]. Hubble data connect the rungs of the cosmic distance ladder to measure the Hubble constant to within 2%, which reveals tensions with cosmic microwave background measurements that new physics could explain[7]. Flagship observatories will continue to have important roles to interpret the multi-messenger signals that include gravitational waves. In the binary neutron star merger event GW170817, the distinct evolution of Chandra's X-ray signature revealed properties of the jet[8], and Hubble spectroscopy provided evidence for its classification as a kilonova[9].

| Year | Hubble | Spitzer | Chandra |
|---|---|---|---|
| 2014 | 817 | 704 | 396 |
| 2015 | 847 | 714 | 426 |
| 2016 | 884 | 614 | 432 |
| 2017 | 911 | 642 | 472 |
| 2018 | 960 | 564 | 448 |
| lifetime | 16332 | 8807 | 7761 |

Table 1: Publications. These three observatories have contributed to over 30,000 refereed publications, with over 100,000 citations to the 2014–2018 publications alone.

The flagship observatories have continued to innovate in operation, offering new observing modes and improving calibration. The latest measurements of the Hubble constant noted above rely on recent more efficient observing

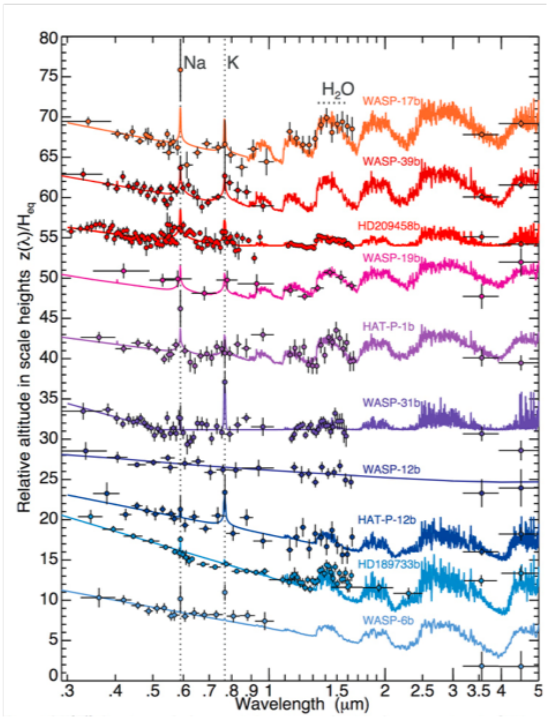


Figure 2: Hubble and Spitzer observations demonstrate the diversity of exoplanet atmospheres. Credit: Sing et al. 2016.

patterns and instrument calibration at the 1% level. Spitzer reengineered its spacecraft operations to provide more than a decade of extended mission operations. Its exoplanet-optimized observing strategies and unique orbit around the sun enabled the discovery of seven earth-sized planets around TRAPPIST-1 nearly eight years after the prime mission ended[10].

Capturing significant photons from the distant Universe and nearby faint objects demands a large scale telescope, especially to elucidate the underlying physics, which usually involves separating the signal (e.g., by position, wavelength, time, or polarization). Gravitational lens modeling of Fe Kα emission from distant quasars observed by Chandra determine disk radii within 2.5 gravitational radii and maximal spin for several high redshift supermassive black holes (SMBHs)[11]. The current flagships have the sensitivity to go beyond the mere discovery of interesting objects to look deeply into populations of sources to probe their formation, structure, and evolution. Multi-wavelength observations of Chandra's deepest observations, the Chandra Deep Field South, (including by Hubble and Spitzer) have provided unprecedented views of SMBHs out to the highest redshifts[12,13].

## Open to the Best Ideas, on All Scales

The flagship space missions democratize science. Through competitive, peer-reviewed access, the best ideas are awarded observations. They are open to all who choose to propose, not restricted to insider access, including scientists at any career stage, at any type of institution, in any location, as individuals or part of large teams. As a result, the total user community numbers several tens of thousands, which would not be equaled by multiples of smaller missions. The transparent processes for using the facilities are inclusive, attracting hundreds of new proposers every annual cycle. The flagships support science at all scales, from small to extremely large, not limited to solving a particular problem. The access remains competitive after decades of operation because the capabilities remain extremely valuable. (Current subscription rates for all exceed 5:1.)

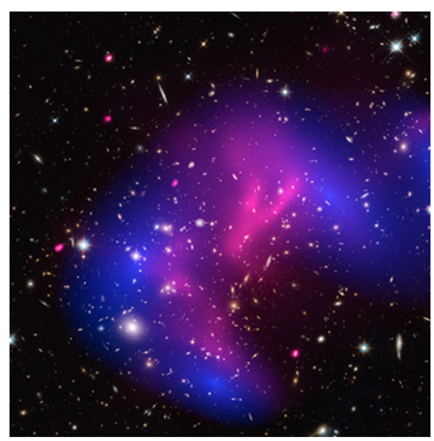

Figure 3: Chandra and Hubble composite image reveals the presence and characteristics of dark matter. Credit: Harvey et al. 2015.

The mission archives are another source of productivity and enable more open access. The systematic observations, well-calibrated instrumentation, and support for a broad archive user community enhance the scientific value of these datasets. The data can be reused multiple times to address different science questions. Today, more than half the Hubble and Spitzer publications are based entirely on archival data, with no involvement of the original proposing team.

## Supporting Community Research

NASA's flagship missions directly support US community research through General Observer programs and Fellowships. US scientists with programs for new observations or related archival and theoretical investigations can receive funding, which enables the completion and publication of the work. This funding is a significant part of the observatory operating budgets (specifically about one-third for Hubble currently). At their peak, these three observatories provided $70 million/year of community funds. These flagship missions also help develop the next generations of scientists. They have been used in over 1000 Ph.D. theses, and currently contribute to over one thesis per week. The NASA Hubble Fellowship Program is part of flagship operations. These Einstein, Hubble, and Sagan Fellows are awarded to some of the most outstanding early-career scientists, engaging them in flagship science, helping them to establish their independent careers, and launching them as future leaders in the field.

## Reaching and Inspiring the Public

The iconic images from current flagship observatories have captured the global public imagination. These are much more than pretty pictures, however, being rooted in the scientific exploration. The many dozens of annual press releases based on scientific results each reach millions of potential readers, with the most popular reaching hundreds of millions. Flagships support a diverse range of outreach activities that increase public engagement with science and technology broadly. They contribute to large-scale events such as the USA Science and Engineering Festival, which attracts over 300,000


Figure 4: Participation in public events can engage thousands at a time, often through immersive experiences, such as virtual reality. Other specialized activities reach distinct groups, such as the blind and visually impaired (right).

participants (Figure 4), and South by Southwest, which regularly has over 70,000 attendees.

## Serving National Interests and International Partnerships

NASA is uniquely able to lead true global flagship space astrophysics missions. International agencies such as the European Space Agency and the Canadian Space Agencies may join as partners, improving the missions, and generally NASA leads the most ambitious endeavors. These and other agencies (including the China National Space Administration) lead development of smaller missions, but only true global flagships will fulfill the needs of frontier astrophysics in the coming decades. Beyond the productivity they directly support, strategic missions inspire and train new generations of scientists and engineers, sustaining and developing a healthy scientific community. They demand innovative technology development, stimulating researchers and industry. As the 2017 National Academies study concluded, "Large strategic missions are essential to maintaining the global leadership of the United States in space exploration and in science."[1]

## Considering Cost and Timescale

Large, strategic missions that deliver the full benefits described above are expensive. We conclude that the investments are worthwhile to enable the transformation science the results from flagships. Large missions must keep costs under control, which they can do by retiring risk early (including through technology development and use of existing technology), maintaining rigorous project management, and having reserves. Large missions remain a critical element of a balanced portfolio. While the NASA Astrophysics budget has not matched the rise of inflation, it must be managed to avoid pushing out other vital components. Figure 5 shows the Astrophysics budget fiscal years 2005 through 2017, where the funding for research and analysis did decline somewhat, but not significantly when strategic mission development spending was large. (These years include portions of Fermi, Hubble, Kepler, Herschel, Planck, JWST, and WFIRST development.)

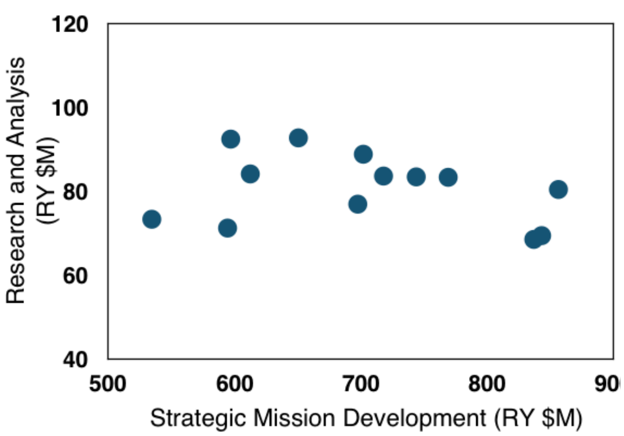


Figure 5: NASA Astrophysics annual budget FY2005–17, Research and Analysis vs. strategic mission development. NASA actively manages the budget to maintain R&A funding and complete mission development.

Flagship science is a multi-decade endeavor. The concepts under discussion now will not deliver science in the 2020s, just as Hubble, Chandra, and Spitzer were each launched more than ten years after the decadal surveys in which they were recommended. Because they address such fundamental science questions and can adapt as those questions change, once operating they remain productive for multiple decades, and the net return is incomparable. The Great Observatories have proven to be especially valuable together by providing simultaneous broad

wavelength coverage. This advantage may be realized over time through long-lasting missions that are managed carefully.

## Strategic Plan Forward

The 2020 Decadal Survey on Astronomy and Astrophysics is already positioned to respond to the key need for strategic flagships. NASA has supported development of mission concepts, which will be evaluated against multiple criteria, including science outcomes, technical feasibility, and cost. The processes are in place to achieve the goal of ensuring that space flagships remain a part of the complete and effective science portfolio.

## Conclusions

The tremendous success of the Great Observatories demonstrates the broad value of flagship space missions. They advance science, engage the public, and drive technology. They stimulate excellence by being inclusive, enabling science at all scales and supporting a broad scientific user community. They open diverse approaches to solve scientific problems and inspire new avenues for discovery. Their systematic archives replicate the rewards through multiple use for new purposes. To fully realize these benefits requires an ambitious portfolio with a commitment to develop and operate genuine flagships, and the result will be the world-leading program that the nation deserves.

The Great Observatories have so essentially shaped the astronomical landscape that we risk taking them for granted. Because of this ambitious program, we have come to expect multi-wavelength observations, funding to support accepted observing programs, open access archives with science-ready data products, broad public appreciation, and bipartisan Congressional support for astronomical endeavors. The field of astronomy and its relationship with the broader world would be fundamentally different had Hubble, Chandra, and Spitzer not existed. Would we be so prepared to ask the critical and far-reaching questions that we know will continue to occupy us for the next ten or twenty years? Would the profession be as vibrant and as dynamic as it is today? Looking ahead to when the current Great Observatories are all retired, will astronomy continue to be enthusiastically supported (publicly, financially, or intellectually) if there are no large strategic missions to serve as the standard bearers for future discovery? We believe the answers to all of these questions are "No," and that in order for the field not just to survive but to thrive the Decadal Survey should be proactive in supporting a continued flagship mission presence in space beyond the James Webb Space Telescope. Reaffirming the importance of flagship missions in a balanced portfolio ensures that the present golden age of astronomy is only a beginning.

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