ASTRO2020 State of the Profession Submission

The Legacy of the Great Observatories: Panchromatic Coverage as a Strategic Goal for NASA Astrophysics

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Abstract

In forthcoming decades, coverage in the wavelength regimes that are either inaccessible or compromised from the ground will be degraded as the Great Observatories and other facilities age or are decommissioned. This reduction in capability will be accompanied by a loss in the community's ability to study astrophysical phenomena at multiple wavelength and temperature regimes, a key to rapid progress, and by an erosion in the technical and scientific expertise in the wavelength regimes that have become out of reach. Expansions of discovery space resulting from new capabilities in some wavelength regimes will be limited by the lack of commensurate data in other regimes. To ensure that multi-wavelength capabilities are maintained, we recommend that NASA consider panchromatic coverage as an explicit strategic goal. Based on the experience of the Great Observatories, a panchromatic goal can be achieved with a mixture of flagship and probe scale missions with lifetimes that exceed a decade, well funded general observer programs for these missions, an active program of smaller space and airborne missions, support for archives, and participation in international space observatories.

1. Introduction

The US astronomical community currently has access to an unprecedented panchromatic capability, extending from the very low frequency radio regime to TeV gamma-rays. NASA's Great Observatories - *Compton, Hubble*, *Chandra*, and *Spitzer* – played a key goal establishing panchromatic access in wavelength regimes that are inaccessible or highly compromised from the ground (Figure 1). The capabilities of the Great Observatories were extended by smaller scale missions such as FUSE, GALEX, SWIFT, FERMI, and NuSTAR, access to European missions such as Herschel, Planck, XMM, and ground-based telescopes functioning within atmospheric windows at visible and radio wavelengths. Our wide-ranging view of the Universe through a multi-wavelength suite of space-based and ground-based observatories greatly expands our ability to discover, and then understand, new phenomena, and to test our theoretical constructs.

The achievement of a panchromatic view of the sky has led to the current golden age of astronomy. Individual observatories are increasingly utilized as a part of a panchromatic system with NASA and other space agencies providing essential access to the IR, UV, X-ray and gamma-ray regimes. This is illustrated pictorially in Figure 2, where we illustrate the wavelength regimes used for current areas of astrophysical research, and in Figures 3-7, which contain specific examples in which multi-wavelength observations from space telescopes were essential for understanding the underlying phenomena. These observatories are supported and utilized by a community with scientific and technical expertise that spans the EM spectrum, whose expertise has developed, to a large degree, through work on NASA's smaller space and airborne missions. The evolution of astronomy from separate disciplines centered on specific wavelength regimes to panchromatic science is a major legacy of the Great Observatories.

ASTRO2020 addresses an immediate future where the Great Observatories are aging, degrading and being decommissioned. *Spitzer* will be decommissioned early in 2020; a number of its capabilities will be superseded by *JWST* which in turn has a 5-10 year lifespan. Compton was decommissioned in 2000 and was partially replaced by Fermi in 2008, which has now passed its planned mission duration. *Chandra* and *Hubble* are 20 and 29 years old, respectively;

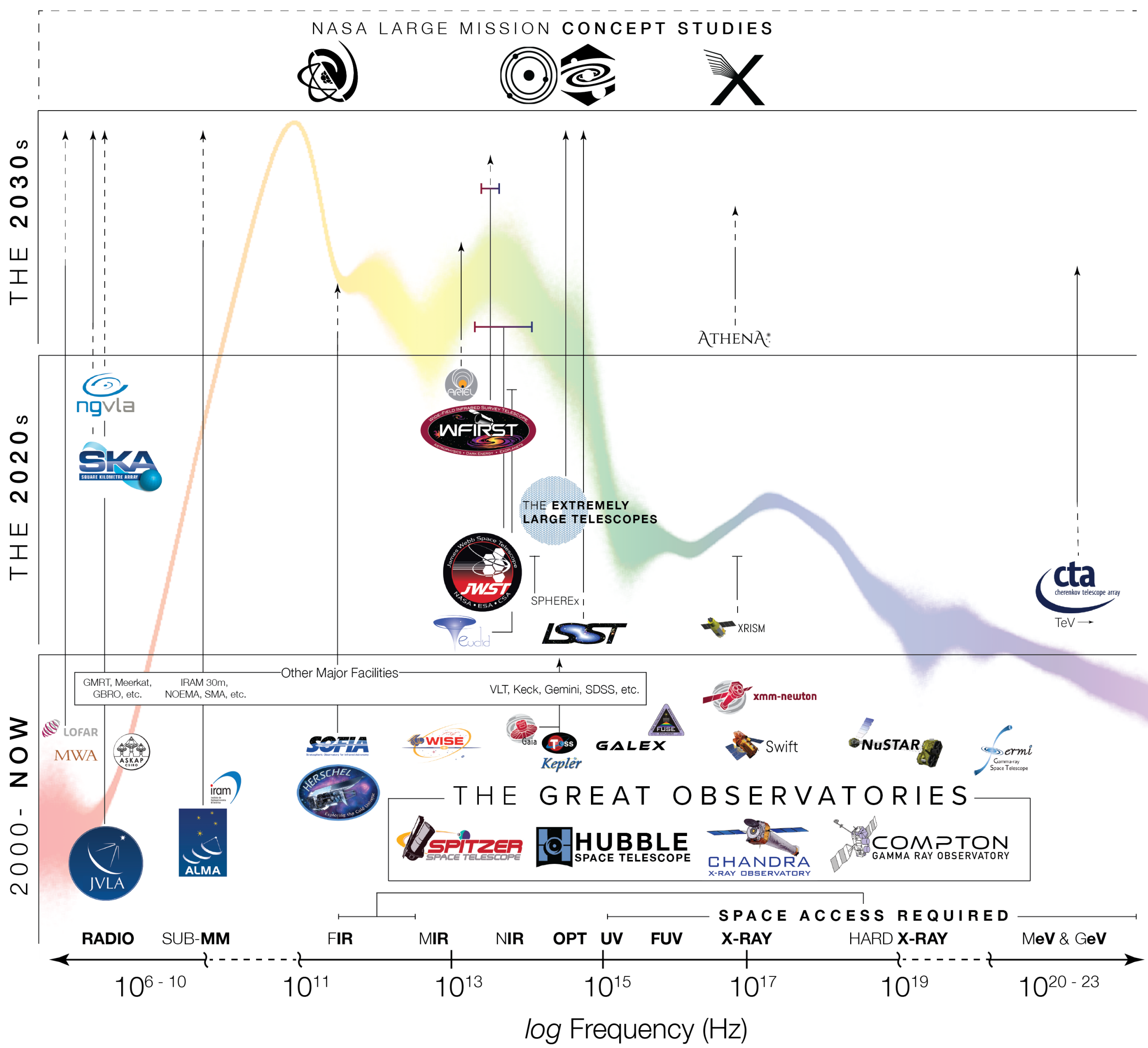

Figure 1: The current and expected coverage of NASA, international and ground-based observatories from 2000 through the 2030s. The widths of the logos do not mark the spectral range covered by each mission; however, the width of the bar at the top of the JWST line gives its wavelength coverage. SOFIA currently provides sole access to the far-IR, yet it cannot achieve the sensitivities of cooled space observatories. The wavelengths covered by OST, LUVOIR, HabEx and Lynx are approximately shown at the top; LUVOIR and HabEx cover similar wavelengths. The total integrated spectrum of the Universe is from Hill et al. (2018).

each is losing capability and could fail at any time. Without strategic planning, the current golden age is in danger of turning into a dark age for astronomy research from space, with major gaps appearing in our electromagnetic coverage, and our ability for cosmic discovery reduced. Considering that multi-wavelength observations will play an essential role in all major research problems confronting the community and prioritized by NASA, maintaining panchromatic capabilities should be elevated to a strategic goal for NASA astrophysics. In this APC

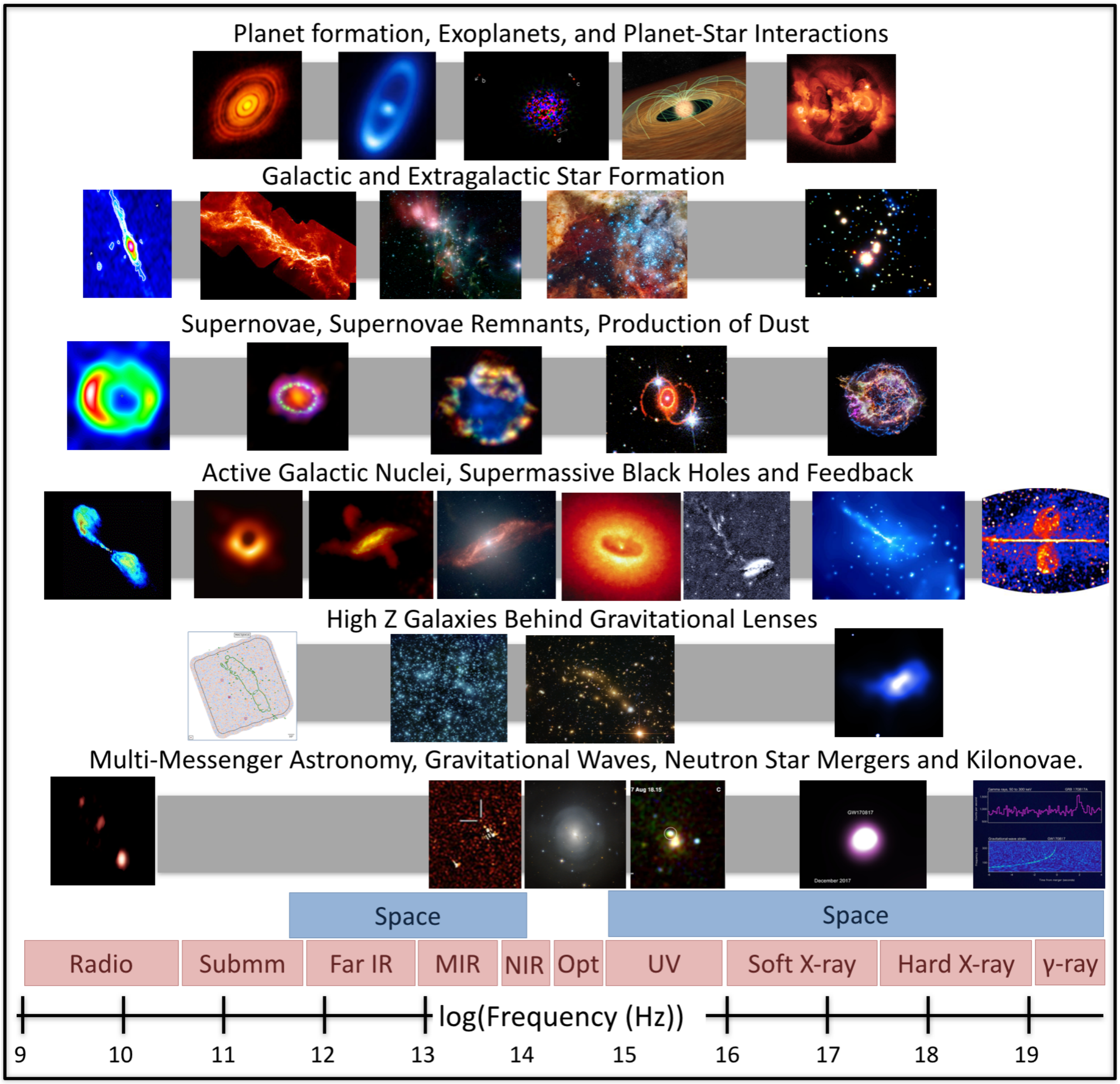

Figure 2: The wavelengths used in current topics in astrophysics. The parts of the spectrum requiring space observatories are marked. These examples demonstrate the importance of panchromatic coverage for studying key astrophysical phenomena.

contribution, we draw lessons from the Great Observatories and make recommendations as to how a strategic goal of panchromatic science can be realized.

2. Impending Gaps

Figure 1 illustrates how wavelength coverage from space will diminish into the 2030's, with forthcoming space-based facilities only partially filling the impending wavelength gaps. Advances in essentially every area of modern astrophysics require multi-wavelength data. Due to

Figure 3: Multi-wavelength observations of the debris disk surrounding Fomalhaut. These data, made with Hubble, Spitzer, Herschel and ALMA, trace dust grains created by collisions within a planetesimal belt extending from 13 to 19 AU around the 2 solar mass star. This belt - although not detected directly - replenishes the grains lost to Poynting-Robertson drag and radiation pressure, as traced by the IR and sub-mm measurements (Stapelfeldt et al. 2004, Acke et al. 2012). The narrow width of the belt may be the result of shepherding by planets (Boley et al. 2012). The IR and visible light measurements with Spitzer and Hubble put tight limits on the masses of the planets, and the Hubble data has detected a planet candidate (Kalas et al. 2005, Marengo et al. 2009, Janson et al. 2012). These data illustrate how multi-wavelength observations map the structure of planetesimal belts, place constraints on the rate of dust production and the properties of the grains, and directly constrain the properties of planets.

the gaps, newly discovered phenomena may have to wait decades for coverage in the IR, UV, X-ray and/or gamma-ray regimes, and time variable astronomical events will lack concurrent observations spanning crucial spectral regimes. The discovery space opened up by the expansion of capabilities in some wavelength regimes will be limited by the lack of commensurate data in other bands. The lack of multi-wavelength coverage will slow our ability to obtain insights needed to develop and refine models of astrophysical phenomena, and they will limit our capability to test and constrain models. Theories supported by one set of observations will not be tested by independent techniques using other wavelengths, leading to “single viewpoint failure” due to lack of challenges to standard models.

A similar erosion will occur in the technical and scientific expertise. If particular spectral bands are not available for decades, students will have little incentive to pursue research in those bands and the phenomena most reliant on the wavelengths they cover. As a consequence, deep knowledge of technologies, techniques and science are not passed on to junior researchers. The progress of future instrumentation develop will also be slowed or become moribund due to the erosion of technical expertise, leading to even slower developments of the technologies needed

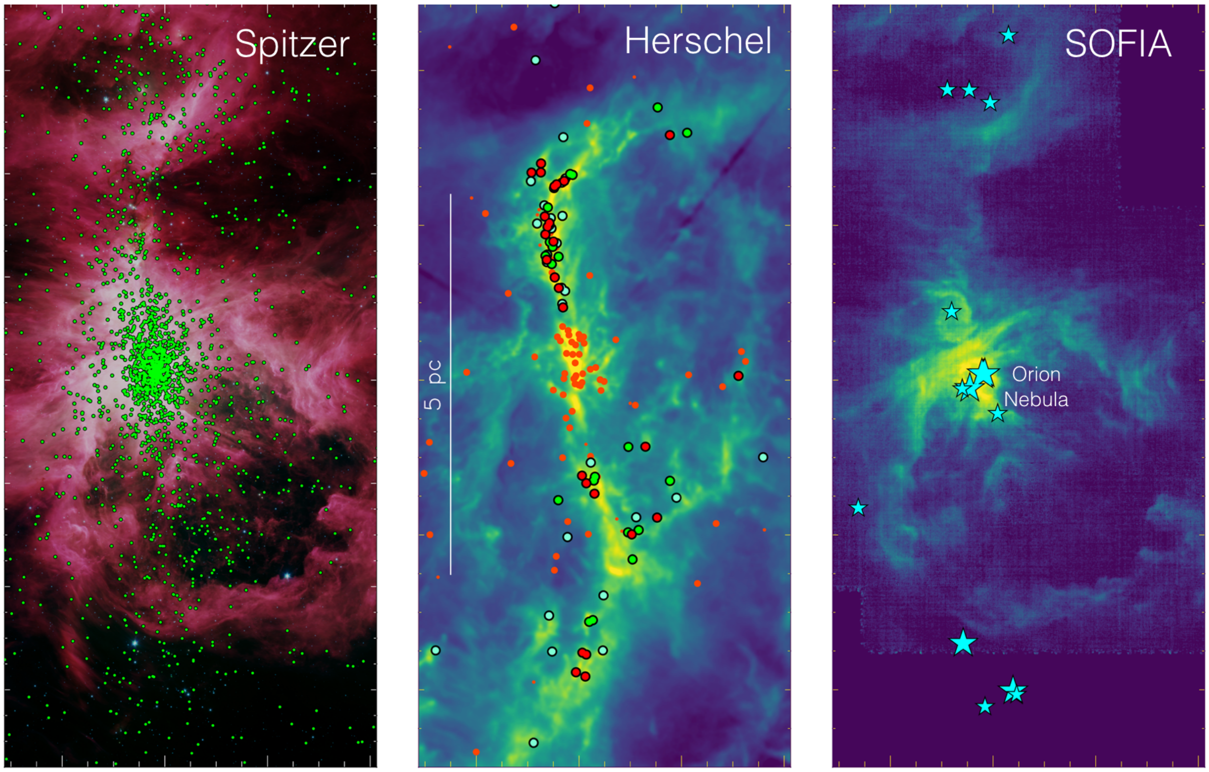

Figure 4 - Wide field surveys of the Orion Nebula Cluster spanning the mid-IR to sub-mm. The data supply a comprehensive evolutionary portrait of the formation of a stellar cluster from a massive filament and the ensuing destruction of the filament. The mid-IR Spitzer image (left) is overlaid with the distribution of the pre-main sequence stars (green dots), these are the stars that formed in the cluster over the last 3 Myr (Megeath et al. 2016). The far-IR/sub-mm Herschel data (middle) maps the massive, dense molecular filament from which the cluster is forming (Stutz & Gould 2016). The positions of the protostars (ages $<$ 0.5 Myr) forming from the filaments are marked; their luminosities and properties are measured by Spitzer and Herschel (Furlan et al. 2016). The feedback from the high mass stars on the parental gas is shown in the [CII] flux map (right) obtained with upGREAT on SOFIA (Pabst et al. 2019), with the positions of the high mass stars overlaid (Brown et al. 1994). Toward the dense center of the cluster, Chandra and Hubble data have mapped the distribution of young stars and measured the impact of the high mass stars on nearby disks (e.g. Bally et al. 1998, Getman et al. 2005). Together these data show the complex network of processes mediating star formation in clusters.

for future missions within the gap regions. Such an erosion raises the prospect of NASA abdicating leadership in neglected space astrophysics disciplines for at least a generation.

3. Lessons from the Great Observatories

The Great Observatories and subsequent multi-wavelength missions provide important lessons on how panchromatic coverage can be achieved, the types of capabilities that are relevant, and how this coverage is utilized by the community. We summarize these here.

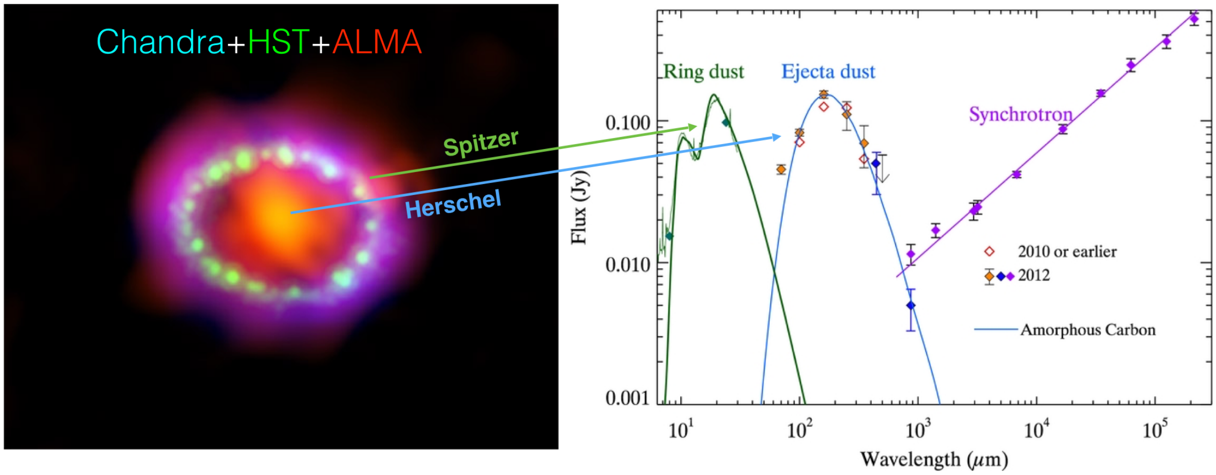

Figure 5 - The X-ray through radio view of SN 1987a. Hubble and Chandra observations resolve the blast wave (left) from the original explosion as it advances into a ring of material expelled by the pre-supernova star (Frank et al. 2016). Spitzer and Herschel data combined with data from ground-based radio telescopes give the SEDs of the supernova from infrared through radio wavelengths (right, McCray & Fransson 2016). While the mid-IR Spitzer observations provide evidence for the destruction of pre-existing dust in the ring of material (Dwek et al. 2008, 2010), the far-IR Herschel observation detect newly formed dust in the debris of the supernova (Matsuura et al. 2011). This dust is spatially resolved by ALMA (Indebetouw et al. 2014); Together these data direct measurement of dust formation and destruction in a supernova, and show that core collapse supernovae may dominate dust production. Left image credited to CXC, ESA, NASA, CfA, Penn State, NRAO and ESO.

The Importance of Commensurability: the study of astrophysical phenomena in multiple wavelength regimes requires commensurate capabilities, or commensurability. These capabilities include sensitivity, mapping speed and coverage, and spatial resolution. The success of the Great Observatories was due in great part to their remarkable degree of commensurability, with different observatories sharing different combinations of capabilities. For example Hubble and Chandra had similar angular resolutions, which were key in studying SN1987a (Figure 5), while Spitzer and Herschel had similar mapping speeds, which were indispensable for studying the Orion Nebula Cluster (Figure 4). Overall, a wide range of phenomena were investigated using Hubble, Chandra and Spitzer due to their commensurate *sensitivities,* as cast relative to energy distributions, despite the lower angular resolution of Spitzer and the slower mapping speeds of Hubble and Chandra. This was crucial for the detection of a z~9 galaxy with Hubble and Spitzer using a gravitational lens (Figure 6). For future missions to achieve large overlap in the phenomena that can be detected and studied, commensurability is essential.

The Importance of Concurrency: the large overlap in the operational lifetimes of telescopes with commensurate capabilities, i.e. concurrency, enabled both unique science and fueled an era of rapid discovery and quickly growing understanding. It allowed for the study of time varying phenomena in multiple spectral regimes; such an approach has proven crucial for studies of

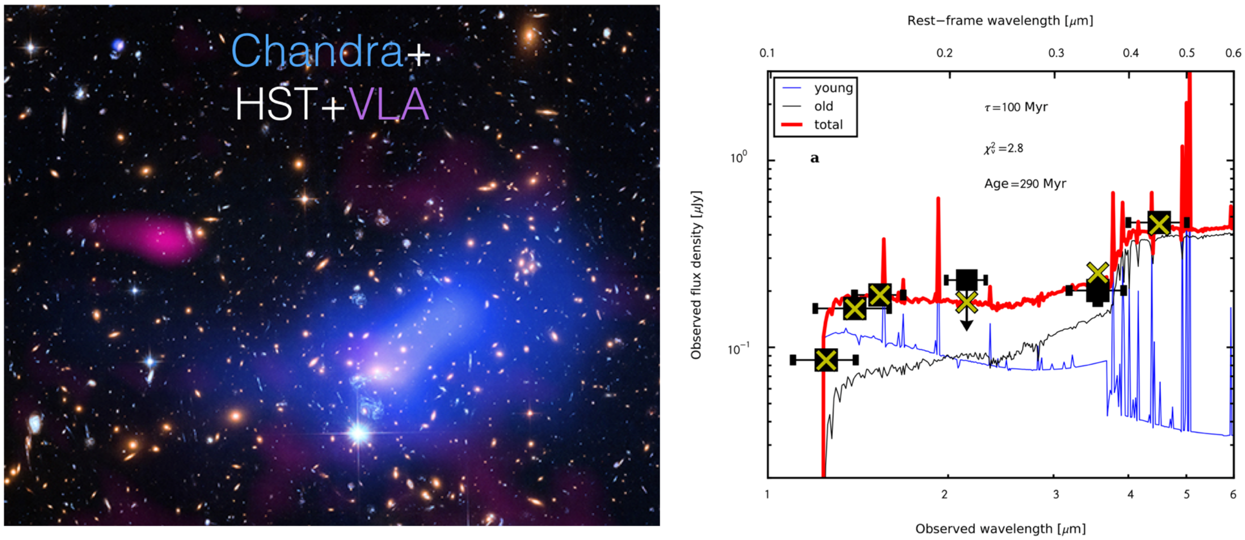

Figure 6 - The star formation history of a z=9.1 galaxy. Using foreground galaxy clusters as gravitational lenses, searches are underway for the earliest galaxies. The properties of the clusters and the lenses are directly measured with Hubble and Chandra data. A redshift z=9.1 galaxy, MACS1149-JD1, was recently found magnified by the cluster MACSJ1149 (left). A detection of the [OIII] 88-micron emission line with ALMA secured the redshift of this galaxy, and helped establish a size and star formation rate (Hashimoto et al. 2018). The galaxy was detected with Hubble, Spitzer, and the VLT, providing rest frame data in the visible and UV regimes (right, from Hashimoto et al. 2018). The multi-wavelength photometric and emission line data suggest that the dominant stellar component of MACS1149-JD1 formed about 250 Myr after the Big Bang, at z~15. These data illustrate how X-ray through sub-mm observations characterize galaxy clusters as well as the distant galaxies made visible via gravitational lensing. Left image credited to CXC, STScI, and NRAO.

supernovae, young star outbursts, gamma ray bursts and AGN (Figure 5). The observations by space observatories at gamma-rays, X-rays, UV, visible, and IR light following the LIGO+Virgo gravitational wave detection of a neutron star merger is an example of concurrent observations that were indispensable for the interpretation of the event and resulting kilonova (Figure 7). Furthermore, by enabling investigations that observe phenomena at multiple wavelengths and sample different temperature regimes, concurrency leads to the more rapid development and testing of astrophysical models (Figures 3-7). Even when operational overlap was impossible, minimizing the temporal gaps between facilities to shorter than a decade, for example that between the cryogenic Spitzer mission and Herschel, led to rapid scientific advances.

General Observer (GO) programs enhance science output and agility: a major strength of the Great Observatories is that the research pursued with these observatories extended far beyond the specific scientific goals adopted during their development. This is in great part due to the well-funded GO programs which empowered these observatories to rapidly adapt to new discoveries and expand into new areas of investigation. As the 2010 Astronomy Decadal report (New Worlds, New Horizons) states: "*It is the combination of improved capabilities and facilities and the resources to use them effectively that has led to the remarkable scientific advances in*

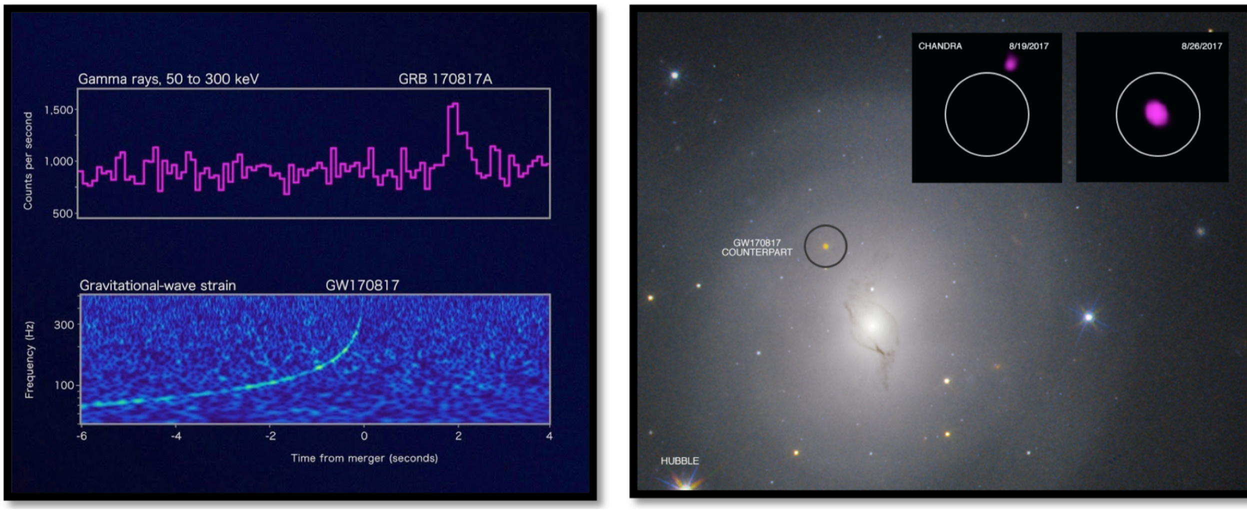

Figure 7 - Multi-messenger astronomy. The joint gravitational wave and gamma-ray detection of the binary neutron star merger GW 170817 / GRB 170817A by LIGO + Virgo and Fermi (left) provided the first multimessenger gravitational wave source and definitive proof that (some or all) short gamma-ray bursts arise from compact object mergers (Abbott et al. 2017). Subsequent imaging with the Hubble (Cowperthwaite et al. 2017) and Chandra detected the ensuing kilonova and jet produced afterglow (Margutti et al. 2017), validating models of kilonovae and their importance for the production of r-process elements. Detections of the kilonova by SWIFT and Spitzer provided evidence of a wind and put constraints on nucleosynthesis by the merger (Evans et al. 2017, Kasliwal et al. 2019). Images: LIGO Laboratory and Chandra X-ray Center.

astronomy." (National Research Council 2010, pg. 5-1). A powerful example is the utilization of Spitzer for exoplanet studies, an area of science that rapidly developed only after it was launched. Another example was the rich range of GO science that flourished during the K2 phase of the Kepler mission, including science on exoplanets, stellar physics, star clusters, young stars, micro-lensing, supernovae, white dwarfs, AGN activity, and solar system objects.

Commensurate missions can span an order of magnitude in cost: the Great Observatories had a wide range of costs, from $1B for Compton and Spitzer, $3B for Chandra, and $9B for Hubble. Technological innovations play a big role in this range. For example, despite the modest size of Spitzer, it had commensurate capabilities due to the development of high efficiency, low noise detector arrays in the IR and the low background of the space environment.

Concurrent development timelines and longevity are needed to achieve observational concurrency: the development times of the Great Observatories ranged from 10 to 20 years. The observational concurrency of these missions was achieved through a combination of concurrent technology development for the different wavelength regimes and the multi-decadal longevity of the observatories: 16 years for Spitzer and 20+ years for Chandra and Hubble.

4. A Strategy for Maintaining Panchromatic Coverage

Without a strategic goal of panchromatic access, major gaps in the coverage of the electromagnetic spectrum will slow astronomical discovery and lead to the erosion of expertise in currently vigorous areas of astrophysics. Maintaining access places fundamental constraints on deployment rates and lifetimes of missions. The number of concurrent observatories is given by

$$N_{obs} = R \times L, \qquad (1)$$

where R is the rate at which new missions are deployed and L is their typical lifetime. The launch of a single flagship mission per decade with a 10 year lifetime would result in only a single operating observatory. Operating five concurrent observatories, equal to that at the peak of the panchromatic capabilities achieved with Fermi, Chandra, Hubble, Spitzer and Herschel, requires a higher rate of deployment and longer mission lifetimes. Based on previous lessons, this can be achieved if we recognize the following points.

A series of missions with a mixture of costs, each with GO programs, can provide commensurate panchromatic capabilities. As with the Great Observatories, not all major advances in discovery space require \$4B - \$10B flagship-class missions. Innovative technologies can produce large improvements in capabilities within a smaller cost envelope. There is much front ranked science that can be done between the cap of explorer missions (\$200M) and the costs of flagship missions (\$4B). Expanding the range of potential mission costs opens up a range of possible strategies to maintain and improve panchromatic coverage. Within the current budget confines, these include launching more modest flagship missions or mixing more costly flagship missions with probe scale (\$1B) missions. These missions would share commensurate capabilities such as sensitivity, angular resolution and/or mapping speed. In the latter case, the probe scale missions should include an extensive GO program; Spitzer and K2 demonstrated the power and feasibility of running GO programs on missions with \$0.5-1B costs.

Panchromatic capabilities should be a mission selection criterion. For a mixture of missions to bring commensurate capabilities across the electromagnetic spectrum, panchromatic science must be an explicit goal in their design and selection. Currently, mission goals are reduced to a series of scientific questions that can be answered by that mission alone, without consideration of how such questions require data across the electromagnetic spectrum. In future missions, commensurate panchromatic coverage should be an explicit goal in itself, and the opportunity costs incurred from gaps in the panchromatic coverage should be considered during mission selection. In this approach, selection is a choice between equal cost alternatives, not just individual missions, where the science gain from one program choice (e.g. one large mission) is weighed against the sum of the science gain from alternatives (e.g. a set of smaller missions) with the same total cost. The inclusion of panchromatic access as an evaluation criterion for mission concepts requires the development of science cases that extend beyond a single mission. This is not without precedent, NASA's Origins and Beyond Einstein programs relied on the deployment of sequences of missions with a range of capabilities and costs.

Small missions play an important role. Active support of panchromatic capabilities also requires the continued development of lower cost observatories in the form of Explorer class missions, sounding rockets, airborne platforms, cube-sats, and small-sats. These missions prototyped new technologies, developed the new scientific and technical expertise required for larger missions, and fostered the next generation of scientists. Small missions also extend panchromatic capabilities and produce sizable science gains through targeted observations (e.g. FUSE, SWIFT and nuSTAR) or by the execution of large surveys (e.g. GALEX and WISE).

Longevity is essential for concurrency. As can be inferred from Eqn. 1, maintaining concurrent multi-wavelength observatories will also require mission lifetimes that exceed a decade. The Great Observatories demonstrated that missions can be operated over multi-decadal timespans, although not without degradation. In the case of Hubble, they also demonstrated that servicing can be used to maintain and upgrade capabilities. The use of servicing, particularly in light of robotic servicing capabilities currently being developed for commercial interests, should be considered as a means for maintaining and enhancing long term multi-wavelength capabilities.

International collaborations will benefit from a panchromatic strategy. Participation in ESA and JAXA missions, such as Herschel, XMM-Newton and Suzaku, has significantly extended the multi-wavelength capabilities available to the US community. Future collaborations are expected to provide access to the US community in wavelength bands not covered by US led missions. A concrete strategic goal of panchromatic coverage would help ensure that participation in such international missions is part of strategic planning, with NASA providing input to the definition of science goals and the mission technologies utilized by these missions.

Archives will play an increasingly important role in panchromatic astronomy. With the growing data archives from the Great Observatories and other missions, NASA maintains a wealth of archival data, including data that covers the sky in wavelength bands from gamma rays to the sub-mm. These data enable unique science, are a foundation for future investigations with more capable missions, and provide baselines for time domain studies. Support for maintaining and enhancing archives is an essential component of panchromatic astronomy. The archives, due to limitations in sensitivity (e.g. WISE), spatial coverage (e.g. Hubble), or angular resolution (e.g. Planck), cannot provide capabilities commensurate to those of newly developed observatories, nor can they provide concurrent capabilities for studying time dependent phenomena. Although an essential part of the panchromatic observing system, the archives are not a replacement for maintaining commensurate, concurrent multi-wavelength observatories.

6. Summary

To maintain access to the electromagnetic spectrum, NASA should establish a strategic goal of enhancing and maintaining commensurate and concurrent panchromatic coverage. This will require that access to the regions of the electromagnetic spectrum that are either inaccessible or compromised from the ground be considered an explicit goal in future mission planning and selection. Science goals that transcend individual wavelength regimes should be developed, and the opportunity costs incurred by potential gaps in the community's access to the electromagnetic spectrum should be considered in strategic planning. Despite the challenges, the example of the Great Observatories demonstrates that deploying and maintaining commensurate and concurrent multi-wavelength coverage is achievable, even within the current confines of NASA's astrophysics budget.

Acknowledgement: the community members who developed this report are contributing to a NASA Science Analysis Group, SAG-10, which will produce a report on multi-wavelength astronomy and the Great Observatories. https://cor.gsfc.nasa.gov/sags/sag10.php

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