Statement of Fiona A. Harrison

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Before the Subcommittee on Space and Aeronautics,
the Subcommittee on Research and Technology
Committee on Science, Space, and Technology
U.S. House of Representatives

December 1, 2021

Mr. Chairman, Madam Chairwoman, Members of the Subcommittee, thank you for the opportunity to appear today to speak to you about *Pathways to Discovery in Astronomy and Astrophysics for the 2020s*, the most recent Decadal Survey of the National Academy of Sciences, which sets a future path for our Nation's Space and Ground Research programs.

My name is Fiona A. Harrison, and I am a professor of physics at the California Institute of Technology, and I chair the Division of Physics, Mathematics and Astronomy. My research involves the study of high-energy phenomena in the Universe, such as the regions near black holes, the dense cores of neutron stars, and regions where particles are accelerated very close to the speed of light. I am both observe these regions using telescopes in space and on the ground, and I develop new technologies and instrumentation for NASA missions. I am the principal investigator of NASA's Nuclear Spectroscopic Telescope Array (NuSTAR), a small explorer mission that observes high energy phenomena in X-rays. In my capacity of division chair, I have academic and administrative responsibility overseeing the research, teaching, academic programs, budget and staff. I testify today in my capacity of co-chair of the National Academy of Sciences' decadal strategy for astronomy and astrophysics, which recently released its report *Pathways to Discovery in Astronomy and Astrophysics for the 2020s.*

The decadal surveys were initiated in the early 1960's with a survey of ground-based astronomy which, with the dawn of the space era, expanded in subsequent reports o include space-based astronomy and astrophysics. The National Academies survey process, which began in astronomy, has been extended to many other fields, including Earth Sciences, Planetary Science and Astrobiology, and Solar and Space Physics. These reports are highly influential for several reasons. First, they involve a very large sector of the relevant community by soliciting input in the form of white papers. Also, the survey committee and its subpanels engage very accomplished, broad leaders spanning all disciplines, who put their personal biases aside to consider the most pressing needs and opportunities. Second, they make hard choices. Of the many hundreds of ideas presented to the survey, only a few will be selected as recommendations to the agencies for implementation. Finally, they provide the Nation with bold visions, but at the same time carefully consider the balance of activities required to build the foundations of the community and its science, forward a vibrant program for the coming decade, and set in motion the frontier facilities that will realize the ambitious science goals of future decades.

Pathways to Discovery in Astronomy and Astrophysics for the 2020s is novel in several ways. This survey was the first to have a dedicated, chartered panel to consider the State of the Profession and Its Societal Impacts. This panel considered many foundational issues, focusing on the urgent need to expand opportunity to Americans from all demographic groups and ethnicities. Because of the appeal of exploring the cosmos, and the broad accessibility of its goals, astronomy and astrophysics is a gateway to Science, Technology Engineering and Medicine. Yet the pipeline is narrow, and there is an urgent need to broaden it to draw from the Nation's entire talent base. The survey has several recommendations targeted at achieving this essential goal. While advancing ambitious future projects, the survey built new mechanisms into the decadal process and agency planning to ensure a sustainable and responsible approach that will enable a broad, ambitious, and balanced scientific program that, once realized will profoundly change the wat that we as humans view our place in the universe.

Executive Summary of Pathways to Discovery in Astronomy and Astrophysics

We live in an extraordinary period of discovery in astronomy and astrophysics. Six Nobel Prizes have been awarded over the past decade alone for discoveries based on astronomical data (dark energy, gravitational waves, neutrino oscillations, the discovery of exoplanets, cosmology, supermassive black holes). Many of the ambitious scientific visions of the 2010 *New Worlds New Horizons*[1] (NWNH) decadal survey are being fulfilled, but momentum has only grown. We stand on the threshold of new endeavors that will transform not only our understanding of the universe and the processes and physical paradigms that govern it, but also humanity's place in it.

This report of the Committee for a Decadal Survey on Astronomy and Astrophysics 2020 (Astro2020) proposes a broad, integrated plan for space- and ground-based astronomy and astrophysics for the decade 2023-2032.[2] It also lays the foundations for further advances in the following decade. This is the seventh in a sequence of decadal survey studies in this field from the National Academies of Sciences, Engineering, and Medicine. This survey examines the program of record, providing advice on the major projects from prior surveys that are yet to be completed. It also lays out priorities for future investments driven by scientific opportunities. The recommendations in this report advance foundational activities that support the people who drive innovation and discovery, and that promote the technologies and tools needed to carry out the science. The report also recommends sustaining activities on a broad range of cost and timescales, as well as activities that enable future visionary projects by maturing them scientifically and technically. Finally, the recommendations set in motion the construction of frontier facilities that will change the view and understanding of the cosmos. The survey is bounded by plausible budget scenarios based on briefings from the sponsoring agencies—the National Aeronautics and Space Administration (NASA), the National Science Foundation (NSF), and the Department of Energy (DOE). Within these bounds, the survey aims high, reflecting this time of great scientific promise and progress, with opportunities to pursue some of the most compelling scientific quests of our times.

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[1] National Research Council, 2010, *New Worlds, New Horizons in Astronomy and Astrophysics*, The National Academies Press, Washington, D.C., https://doi.org/10.17226/12951.

[2] The statement of task specified a date range of 2022-2032. This has been adjusted to more accurately reflect the range that the Survey will affect.

THE SCIENTIFIC OPPORTUNITIES

The survey's scientific vision is framed around three broad themes that embrace some of the most exciting new discoveries and progress since the start of the millennium, and that promise to address some of the most fundamental and profound questions in our exploration of the cosmos. The first theme, *Worlds and Suns in Context* builds on revolutionary advances in our observations of exoplanets and stars and aims to understand their formation, evolution, and interconnected nature, and to characterize other solar systems, including potentially habitable analogs to our own. *New Messengers and New Physics* will exploit the new observational tools of gravitational waves and particles, along with temporal monitoring of the sky across the electromagnetic spectrum and wide-area surveys from the ultraviolet and visible to microwave and radio to probe some of the most energetic processes in the universe and also address the nature of dark matter, dark energy, and cosmological inflation. Research in the third theme, *Cosmic Ecosystems,* will link observations and modeling of the stars, galaxies, and the gas and energetic processes that couple their formation, evolution, and destinies.

Within each of these broad and rich scientific themes, three priority areas motivate recommended investments over the coming decade. "Pathways to Habitable Worlds" is a step-by-step program to identify and characterize Earth-like extrasolar planets, with the ultimate goal of obtaining imaging and spectroscopy of potentially habitable worlds. "New Windows on the Dynamic Universe" is aimed at combining time-resolved multi-wavelength electromagnetic observations from space and the ground with non-electromagnetic signals to probe the nature of black holes, neutron stars, the explosive events and mergers that give rise to them, and to use signatures imprinted by gravitational waves to understand what happened in the earliest moments in the birth of the universe. "Unveiling the Drivers of Galaxy Growth" is aimed at revolutionizing our understanding of the origins and evolution of galaxies, from the nature of the tenuous cosmic webs of gas that feed them, to the nature of how this gas condenses and drives the formation of stars.

THE RECOMMENDED PROGRAM

Major leaps in observational capabilities will be realized in the coming decade when new large telescopes and missions commence science operations (Table 7.1). Recommended by previous surveys, with some undertaken with international partners, these projects and programs are an essential base upon which the survey's scientific vision is built. It is essential that these initiatives be completed, and the scientific programs be supported at levels that ensure full exploitation of their potential by the U.S. scientific community.

Going forward, this survey lays out a strategy for federal investments aimed at paving a pathway from the foundations of the profession to the bold scientific frontiers.

Large Programs that Forge the Frontiers

These scientific visions—Pathways to Habitable Worlds, New Windows on the Dynamic Universe, and Unveiling the Drivers of Galaxy Growth— require the major recommended investments in large projects to begin design and construction in the coming 10 years (Tables S.5

and S.6; Figure S.1).[3] In space, achieving the community's most ambitious and visionary ideas in a sustainable way, and realizing the broad capabilities demanded by the richness of the science, requires a re-imagining of the ways in which large missions are planned, developed, and implemented. The **Great Observatories Mission and Technology Maturation Program** (Table S.5) would provide significant early investments in the co-maturation of mission concepts and technologies, with appropriate decadal survey input on scope, and with checks and course corrections along the way. Inspired by the vision of searching for signatures of life on planets outside of the solar system, and by the transformative capability such a telescope would have for a wide range of astrophysics, the survey recommends that the first mission to enter this program is a **large (~6 m aperture) infrared/optical/ultraviolet (IR/O/UV) space telescope.** The scientific goals of this mission, when achieved, have the potential to profoundly change the way that human beings view our place in the universe. With sufficient ambition, we are poised scientifically and technically to make this transformational step. This endeavor represents a quest that is on the technical forefront, is of an ambitious scale that only NASA can undertake, and it is one where the United States is uniquely situated to lead the world. If maturation proceeds as expected, the survey recommends that formulation and implementation begin by the end of the 2020 decade. To prepare for future large, strategic missions, 5 years after beginning the maturation program for the IR/O/UV mission, the survey recommends commencing mission and technology maturation of both a far-IR and an X-ray large strategic mission, both scoped to have implementation costs in the $3 billion to $5 billion range.

Because of the powerful potential that large (20–40 m) telescopes with diffraction-limited adaptive optics have for astronomy, and because of the readiness of the projects, the survey's priority for a frontier ground-based observatory is a significant U.S. investment in the Giant Magellan Telescope (GMT) and Thirty Meter Telescope (TMT) projects, ideally as components of a coordinated **U.S. Extremely Large Telescope Program (ELT) program**. These observatories will create enormous opportunities for scientific progress over the coming decades and well beyond, and they will address nearly every important science question across all three priority science areas. After this, given technical and scientific progress over the last decades, ground-based cosmic microwave background (CMB) studies are poised in the next decade to make a major step forward, and the **CMB Stage 4 (CMB-S4) observatory** (with support from NSF and DOE) will have broad impact on cosmology and astrophysics. It is also essential to astronomy that the Karl Jansky Very Large Array (JVLA) and Very Long Baseline Array (VLBA), which have been the world-leading radio observatories, be replaced by an observatory that can achieve roughly an order of magnitude improvement in sensitivity compared to those facilities. **The Next Generation Very Large Array (ngVLA)** will achieve this, with a phased approach where design, prototyping, and cost studies are completed and reviewed in advance of commencing construction. Finally, neutrino observations are important to understanding some of the most energetic processes in the universe, and the Ice Cube-Generation 2 (IceCube-Gen2) observatory will make advances in important astrophysics questions, although it is beyond the charge of this survey to recommend it.[4]

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[3] For space, large projects are defined as those with costs exceeding $1.5 billion. For ground-based initiatives, large projects are defined as those exceeding $130 million for the total program investment.

[4] IceCube is supported and managed by the NSF Division of Physics, rather than the Division of Astronomical Sciences.

Programs that Sustain and Balance the Science

Turning to medium-scale missions and projects, the scientific richness of a broader set of themes—exploring *New Messengers and New Physic*s, understanding *Cosmic Ecosystems*, and placing *Worlds and Suns in Context*—as well as the need to capitalize on major existing investments and those coming online in the next decades drive the essential sustaining projects (Tables S.5 and S.6). In space, the highest-priority sustaining activity is a **space-based time-domain and multi-messenger program** of small and medium-scale missions. In addition, the survey recommends a new line of probe missions to be competed in broad areas identified as important to accomplish the survey's scientific goals. For the coming decade, a far-IR mission, or an X-ray mission designed to complement the European Space Agency (ESA's) Athena mission, would provide powerful capabilities not possible at the Explorer scale. With science objectives that are more focused compared to a large strategic mission, and a cost cap of $1.5 billion, a cadence of one probe mission per decade is realistic. The selection of a probe mission in either area would not replace the need for a future large, strategic mission. For ground-based projects, the highest-priority sustaining activity is **a significant augmentation and expansion of mid-scale programs**, including the addition of strategic calls to support key survey priorities. The survey also strongly endorses investments in **technology development for advanced gravitational wave interferometers**, both to upgrade NSF's Laser Interferometer Gravitational-Wave Observatory (LIGO), and to prepare for the next large facility.[5]

Foundational Activities

A successful decadal survey strategy requires serious attention to the smaller but vital investments in the foundations of the research. The people who make up the profession are the most fundamental component of the research enterprise, without whom the ambitious facilities, instruments, and experiments, as well as the promised transformative discoveries, would lie unfulfilled. Recognizing that diversity is a driver of innovation, and that the astronomy and astrophysics enterprise can be at its most innovative only when it maximizes and fully utilizes the broadest range of human talent, the survey forwards several crucial programs (Table S.1) to support early-career entrants, with a strong emphasis on broadening access, removing barriers to participation, and creating an environment that eschews harassment and discrimination of all kinds. The future of the field also requires that greater attention be paid to issues of sustainability and accountability, and several recommendations address these issues. Among the recommendations regarding the state of the profession, the most urgent need is maintenance of accurate data on funding outcomes, because it is sufficiently critical to the other recommendations. (Table S.1).

Science cannot progress without the essential support to individual investigators who take the data and transform them into scientific understanding and discovery. Accordingly, augmenting the NSF Astronomy and Astrophysics Grants program is the highest priority among the foundational recommendations. Science also cannot progress without the necessary tools, such as archives, data pipelines, laboratory work, and theoretical tools that provide the essential, cross-cutting foundations. The computational revolution continues to transform the conduct and

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[5] Technology development for gravitational wave detection is funded out of the NSF Division of Physics. The survey strongly endorses the importance of the science to astronomy and astrophysics.

culture of astronomy through the growing roles of large surveys and shared public data sets, big-team research, applications of machine learning, and numerical simulations, among others, and research investments will need to evolve to adapt to this changing landscape. Several critical areas require a healthier balance in order to optimize the scientific returns on past and future major investments (Table S.2).

The currently operating facilities on the ground and in space, along with the scientists who use them, are the primary engines of scientific discovery and progress in astronomy and astrophysics. In this regard, it is essential to adequately support the costs of operating facilities in space and on the ground, review them regularly during their productive lives, and for ground-based observatories, maintain them as premier facilities with modern, state-of-the-art instrumentation. Table S.3 summarizes this report's recommendations relative to the agencies' operational portfolios.

A balanced portfolio that includes a healthy investment in small- and medium-scale projects that are competed, draws from the ingenuity and breadth of the community, and enables science on a broad range of costs and timescales is essential for sustaining a vibrant astronomy and astrophysics program. These activities sustain scientific progress, amplify and enhance return from operating missions and observatories, and respond nimbly to new discovery. The survey recognizes the foundational need for supporting basic technology development and the crucial role small- and medium-scale projects play in broadening science and as a means of developing the next generation of technologists and instrumentalists. Table S.4 summarizes recommendations aimed at strengthening these.

Enabling Future Visions

The community's most ambitious and visionary ideas now require timelines that are pan-decadal and even multi-generational. This is particularly true for NASA's large strategic missions and NSF's premier observatories that are driven by transformative scientific visions but are technically challenging. They also represent large investments of resources. Optimizing the cadence of major facilities and developing them in a sustainable way that ensures the appropriate level of maturity prior to a decadal or agency commitment and tighter control on ultimate project costs requires new, enabling programs and approaches. The Great Observatories Mission and Technology Maturation Program would provide a new approach for developing large space strategic missions. In addition, for all large projects, the survey provides decision rules and recommends reviews, where required, to ensure technical, scientific, and cost-readiness prior to commitment of major resources. The survey also identifies a few future projects that are targets for significant investment in maturation for consideration by future decadal surveys.

A very large fraction of the astronomical community contributed to this survey through the almost 900 excellent science, activity, program, and state of the profession white papers and through active engagement in town hall meetings. The program laid out in this report represents a collective vision for the future and will require the engagement of a broad community to advance.

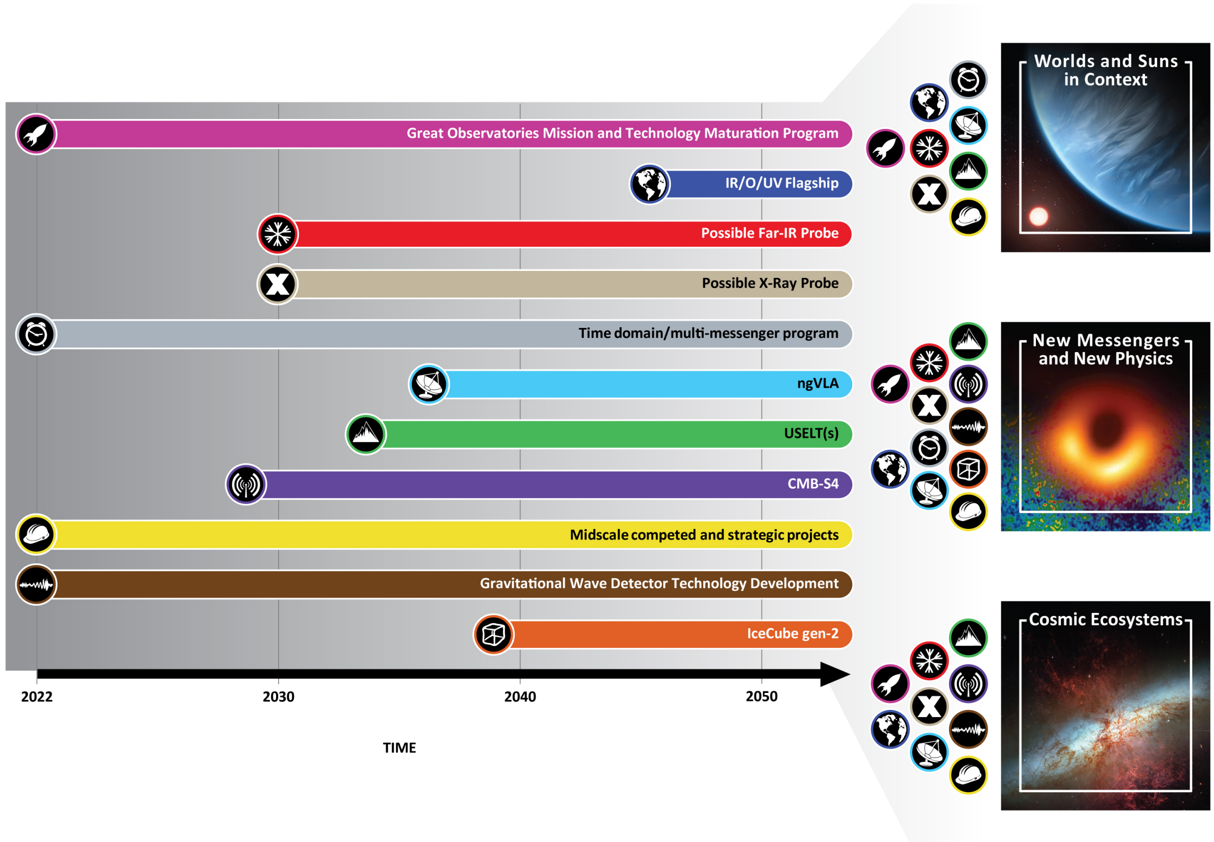

FIGURE S.1 Timeline for the recommended medium and large programs and projects. The starting point of each, indicated by the logos, shows the projected start of science operations for missions and observatories, or the start date of the program. The boxes on the right show the survey's three broad science themes, and the placement of the logos to the left of the boxes indicate which activities address the indicated theme.

Prof. Fiona Harrison

Curriculum Vitæ

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Current Position

2015-present **Kent and Joyce Kresa Leadership Chair**, Division of Physics, Mathematics and Astronomy, California Institute of Technology.

2013-present **Harold A. Rosen Professor of Physics**, California Institute of Technology.

Education

1993 **PhD**, *Physics*, University of California, Berkeley, Berkeley, CA.

1985 **AB**, *Physics, with honors, Magna cum laude*, Dartmouth College.

Previous Positions

2005-2013 **Professor of Physics**, Caltech.

2001-2005 **Associate Professor of Physics**, Caltech.

1995-2001 **Assistant Professor of Physics**, Caltech.

1993-1995 **Robert A. Millikan Prize Research Fellow**, Caltech.

1988-1993 **Research Assistant**, Space Sciences Laboratory, Department of Physics, U.C. Berkeley.

Honors and Awards

2020 **Hans Bethe Prize**, American Physical Society.

2020 **Fellow**, American Astronomical Society.

2016 **Harrie Massey Award**, Committee on Space Research.

2015 **Bruno Rossi Prize**, American Astronomical Society.

2015 **Honorary Fellow**, Royal Astronomical Society.

2014 **Member**, National Academy of Sciences.

2014 **Fellow**, American Academy of Arts and Sciences.

2013 **NASA Outstanding Public Leadership Medal**.

2012 **Fellow**, American Physical Society.

2010 **Doctor Technices Hornoris Cuasa**, Danish Technical University.

2008 **Named one of America's Best Leaders**, U.S. News and Kennedy School of Government.

2000 **Presidential Early Career Award**.

1989 - 1992 **NASA Graduate Student Research Fellow**.

Presentations (selected)

Invited Prize Positions and Named Lectures

2019 **Manne Siegbahn Memorial Lecture**, Stockholm University.

2016 **Edwin Salpeter Lecturer**, Cornell University.

2015 **Celia Payne-Gaposchkin Lecture**, Harvard-Smithsonian Center for Astrophysics.

2014 **Lyman Spitzer Lecturer**, Princeton University.

2014 **International Senior Research Fellowship**, Durham University.

2014 **Sackler Distinguished Visitor**, Institute of Astronomy, Cambridge UK.

2013 **John Bahcall Memorial Colloquium**, Weizmann Institute, Israel.

Public Lectures

2019 **U.C. Berkeley Astronomy Distinguished Public Lecture**.

2017 **Helen Sawyer Hogg Lecture**, Canadian Astronomical Society.

2014 **Watson Lecture**, Caltech.

2012 **von Kármán Lecture**, Pasadena Community College Auditorium, Sponsored by JPL.

Leadership and National Service (Selected)

2020-present **Chair**, *High Energy Astrophysics Division of the AAS*.

2019-present **Co-Chair**, Decadal Survey on Astronomy and Astrophysics.

2019 **Member**, *James Webb Space Telescope Independent Review Board*.

2017-2019 **Chair**, *Space Studies Board of the National Academy of Sciences*.

2017 **Chair**, *Division of Astrophysics, American Physical Society*.

2009-2010 **Member**, *Decadal Survey on Astronomy and Astrophysics Steering Committee*.

Current Research Interests

PI, NuSTAR Mission: I led the technology, development, launch and prime mission of this NASA Small Explorer. The extended mission is now serving the community through a GO Program

Observational Interests: Studies of accreting black holes, neutron stars, and ultraluminous X-ray sources, explosive astrophysical transients, supernova remnants in high-energy X-rays and radioactivity, the evolution of supermassive black holes.

Technology Development: I am leading technology programs aimed at developing next-generation imaging and spectroscopic detectors for X-ray missions, and the development of CMOS detectors for UV space astrophysics applicaitions

Mentorship

Graduate Students: Peter Mao (PhD 2002), Sarah Yost (2004), Megan Eckart (2006), Hubert Chen (2008), Brad Cenko (2008), Varun Bhalerao (2012), Mislav Baloković (2017), Yanjun Xu (2021), Nikita Kamraj (2021), Sean Pike, Myles Sherman.

Postdocs: Aleksey Bolotnikov, Steve Boggs (Millikan Fellow), Wayne Baumgartner, Kristin Madsen, Brian Grefenstette, Dominic Walton, Felix Fuerst, Liz Rivers, Murray Brightman, Hannah Earnshaw, Javier Garcia, Marianne Heide, Renee Ludlam (HST Fellow), Amruta Jaodad, Riley Connors, Margaret Lazzarini (NSF Fellow).

Undergraduate Research Students: More than 75 summer undergraduate researchers have completed projects in my group, including 17 WAVE Fellows (providing opportunities for URMs in STEM).

Ten Most Significant Publications (as if 9/2021, time-ordered after most cited)

1 **Harrison et al.** 2013, *"The Nuclear Spectroscopic Telescope Array"*, ApJ, 770, 103, (1192 citations).

2 **Evans et al.** 2017, *"Swift and NuSTAR observations of GW170817: Detection of a blue kilonova"*, Science, 358, 1565, (299 citations).

3 **Boggs, Harrison et al.** 2015, *"44-Ti gamma-ray emission lines from SN1987A reveal an asymmetric explosion"*, Nature, 348, 670, (82 citations).

4 **Harrison et al.** 2015, *"The NuSTAR extragalactic surveys: The number counts of active galactic nuclei and the resolved fraction of the cosmic X-ray bacground"*, ApJ, 831, 185, (52 citations).

5 **Bachetti, Harrison et al.** 2014, *"An ultraluminous x-ray source powered by an accreting neutron star"*, Nature, 514, 7521, (454 citations).

6 **Grefenstette, Harrison et al.** 2014, *"Asymmetries in core-collapse supernovae from maps of radioactive Ti-44 in Cassiopeia A"*, Nature, 506, 339, (161 citations).

7 **Risaliti, Harrison et al.** 2013, *"A rapidly spinning black hole at the centre of NGC1365"*, Nature, 494, 449, (221 citations).

9 **Yost, Harrison et al.** 2003, *"A study of the afterglows of four gamma-ray bursts: Constraining the explosion and fireball model"*, ApJ, 59, (213 citations).

8 **Harrison et al.** 2001, *"Broadband observations of teh afterglow of GRB 000926: Observing the effect of inverse Compton scattering"*, ApJ, 559, 123, (122 citations).

10 **Harrison et al.** 1999, *"Optical and radio observations of the afterglow from GRB 990510: Evidence for a jet"*, ApJ, 523, 2, (256 citations).

369 refereed publications, h-index = 69