Astro2020 Science White Paper

Increasing the Discovery Space in Astrophysics The Exploration Question for Compact Objects

Thematic Areas: Formation and Evolution of Compact Objects
Multi-Messenger Astronomy and Astrophysics

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Abstract:

We write in response to the call from the 2020 Decadal Survey to submit white papers illustrating the most pressing scientific questions in astrophysics for the coming decade. We propose exploration as the central question for the Decadal Committee's discussions. The history of astronomy shows that paradigm-changing discoveries were not driven by well-formulated scientific questions, based on the knowledge of the time. They were instead the result of the increase in discovery space fostered by new telescopes and instruments. An additional tool for increasing the discovery space is provided by the analysis and mining of the increasingly larger amount of archival data available to astronomers. Revolutionary observing facilities, and the state-of-the-art astronomy archives needed to support these facilities, will open up the universe to new discovery. Here we focus on exploration for compact objects and multi-messenger science.

1. The exploration question

There has been a long-standing tension in our discipline between the 'exploration' approach and the more physics-based 'question-driven' approach.

1.1 - *The **question-driven** approach*

This approach seeks to formulate the most important open questions in our discipline. It is based on our *present knowledge* of the field (both theoretical and observational) and is formulated usually as a way to constrain and/or advance a currently proposed cosmological or astrophysical scenario. 'Question/hypothesis-driven' has been the preferred approach in the last few decades and is used to justify both observing proposals and proposals for new instruments and telescopes. Most talks at conferences and papers are framed based on this question and answer approach. This is how we teach our students to approach research. This is the approach formulated in the Decadal Survey call for white papers. This approach addresses the '*known unknowns*': for example, the way to best constrain the cosmological parameters of our universe, and lately the search for dark matter and dark energy, and the definitive discovery of gravitational waves.

The question-driven approach continues to be fruitful, and it gives us a certain sense of control in our progress, but -by its own nature- is also a limited and limiting epistemology. For example, it can bias our knowledge. As expounded in a recent article with reference to extra solar planets "the key is to make sure that science policy permits discovery for the sake of discovery and not for finding Earth-like planets, which we have prejudiced to be of greatest interest (D. J. Stevenson, CalTech, Physics Today, Nov. 2018)". The same opinion can be easily shaped to apply to other fields of astrophysics.

The question-driven approach does not address the *'unknown unknowns'* that by their nature cannot be addressed as well-defined 'important questions'.

1.2 - *The **exploration** approach*

This approach, i.e. gaining the capability to find new questions, rather than solving known ones, is the only way we can address the *unknown unknowns*. Harwit (1984) calls this '*discovery space*'. The notion that most of science is undiscovered and that 'out of the book' thinking may be needed for real progress is making fast inroads (e.g., see the book 'Ignorance: How it Drives Science' by S. Firestein, 2012). How to best foster the discovery of *unknown unknowns* is particularly poignant for astronomy, which throughout its history has been first and foremost exploratory.

The real big paradigm shifts in astronomy and astrophysics have occurred when new approaches have significantly opened up the discovery space, revealing unforeseen views of the universe. These approaches may have been framed as a way to address important questions of the time, but the real advances were from serendipitous discoveries. The discovery space may have been increased by means of new telescopes and instruments (both hardware and software), and also by *unanticipated data repurposing*.

Famous examples of discoveries stemming from exploration include:

- The Galilean Moons of Jupiter, the metal composition of the Sun and stars, the HR diagram, the expansion of the Universe, large scale structure, hot Jupiters (driven by improvements in optical telescopes and spectrographs);
- Quasars, radio galaxies, the microwave background, pulsars, superluminal motion, fast radio bursts (following the invention of radio telescopes, VLBI, and search in the archives in the case of bursts);
- Black holes and their mass range, dark matter, dark energy, super-starburst galaxies (from the availability of new space-based observing windows, X-ray, IR, and high resolution optical imaging with HST, and availability of multi-wavelength archives).

These foundational discoveries for the present understanding of the Universe and its evolution were not in any way anticipated. Most of them were fostered by the use of increasingly larger telescopes and more sensitive instruments, able to explore different parts of the electromagnetic spectrum. Others were surprising results of the data analysis.

Given the increasing availability of large and survey data sets in our open archives, a new hybrid approach, **question-driven exploration**, has emerged, where astronomers have mined these data and researched the literature guided by relatively vague questions, finding answers, new questions, and surprises. A similar approach is making inroads in biology (Elliott et al 2016).

In this white paper we discuss the '*exploration question'*, providing examples relevant for the field of compact objects. We include both serendipitous discoveries and question-driven explorations, resulting from unanticipated analyses of multi-wavelength survey data (Section 2). In Section 3, we address our recommendations for increasing the discovery space.

2. Exploration in Compact Objects

Given the nature of exploration, it is not possible to give definite questions that need to be addressed in the near future. Rather, we provide a few examples of (1) serendipitous unexpected discoveries (*unknown unknowns*) and their potential for changing established paradigms; and (2) new research avenues posed by asking very general questions (*known unknowns*). We do not mean to provide an exhaustive survey of such discoveries, but only to illustrate our case with a few representative studies.

Although there were a few theoretical predictions beforehand, compact objects are excellent exemplars of discoveries made through exploration. In the space of a few years, *neutron stars* were found both as pulsars, seen as "scruff" in radio survey data (Hewish, Bell et al. 1968), and as bright periodic X-ray sources; *black holes* were found as rapidly variable X-ray sources and, later, dynamically with spectroscopy of the secondaries of faded X-ray transients (McClintock and Remillard 1986). *Gamma-ray bursts* discovered at the same time (Klebesadel et al., 1973) were mysterious for decades but also implied compact objects. *Fast radio bursts* are a more recent discovery and may be connected with compact objects.

In addition to being *totally unexpected discoveries*, compact objects (including stellar-mass black holes and neutron stars), required observations at wavelengths other than the wavelength of their discovery (typically X-ray, radio or gamma-ray) before their true nature could be determined. An explanation for radio pulsars was developed within months of their discovery (Gold 1968), for X-ray binaries within years of discovery (Pringle & Rees 1972), and for gamma-ray bursts we are only now, more than half a century later, beginning to understand their nature:

- Radio pulsars provided us with the first (indirect) evidence for the existence of *gravitational waves*. Pulsar glitches led to the recognition of solid crusts on *neutron stars*, and neutron stars offer ways to test the nature of the strong nuclear force via their equation of state.

- X-ray binaries use the most efficient means known of extracting energy from matter. Their messy phenomenology revealed its hidden order when color-color and color-intensity diagrams from archival data showed clear paths between different accretion states (Done & Gierlinski 2003), reflecting the balance of disk and jet emission as accretion rates change.
- The known mass range of stellar *black holes* was greatly extended by LIGO *gravitational wave* detections (Abbott et al 2017a). Joint observations of gravitational wave signal GW170817 by the LIGO-Virgo detector network and transient electromagnetic counterparts from multiple telescopes resulted in a triumph for multi-messenger astronomy: discovery of an inspiraling binary neutron star (Abbott et al. 2017b).
- Bright X-ray bursts (discovery paper, Grindlay, Gursky et al 1976) are energetic phenomena typical of accreting neutron stars in binaries, associated with thermonuclear flashes on the NS surface (see e.g., review Lewin et al 1995).
- Gamma-ray bursts, which are the most energetic phenomena known to humanity, have been connected with neutron star mergers, resulting in the first *multi-messenger* observations of *gravitational wave* events (e.g., Haggard, et al., 2017). Multi-wavelength light curves can provide a physical view of the phenomenon (Kasliwal et al. 2017).
- Fast Radio Bursts are transient phenomena lasting only milliseconds, are suspected of being compact objects, and many are being discovered by an instrument designed to look for redshifted 21cm hydrogen emission (Chime/FRB Collaboration 2019). There are dozens of ideas about what they *might* be, but no way to discern between them. FRBs may provide new cosmological tests (Jaroszynski, 2019).

The archival data available at different wavelengths provide a resource for exploration, both for identifying new phenomena that may be related to compact objects, finding precursor objects, and investigating systematics in newly identified classes. For example:

- A blind search for pulsations of 13 years of XMM observations containing 50 billion photons led to the discovery of the first *extragalactic X-ray pulsar* in a globular cluster and the first pulsar in the Andromeda galaxy, which is also the second slowest X-ray pulsar known (p=1.2sec, Zolotukhin et al., 2017). This long period challenges theories of binary star formation and evolution in clusters, as it must have started accreting recently, about 1 Myr ago, yet is hosted in a 12 Gyr-old globular cluster.
- Archival searches for *fast radio bursts* are ongoing and beginning to produce results (e.g., Zhang et al., 2019).
- Spectral and timing properties of populations of X-ray sources discovered with *Chandra* in nearby galaxies have been used to compare them with the known behavior of compact Galactic binaries. Color-color-intensity diagrams were used to separate classes of X-ray binary (black holes and neutron stars) and to separate jet-producing versus non-jet-producing XRBs. This is directly akin to color-magnitude, Hertzprung-Russell diagrams for stars, which was also unanticipated (Vrtilek & Boroson 2013).
- Comparison with *Hubble* imaging and photometry have led to extraction of globular cluster binaries; association of binaries with different stellar population age and metallicity; and even to the realization that both globular clusters and X-ray binaries may trace merging accretion events in giant elliptical galaxies. These comparisons have led to constraints on the nature of these sources and their evolution (e.g., see reviews: Fabbiano 2006; 2019).

The identification of fast timing events at different wavelengths will also require *archival databases* for studying the baseline state and past history of the associated object. As a case in point, researchers racing to find an optical counterpart to binary neutron star merger GW170817 made use of NED to point the Swope telescope and discover an afterglow in lenticular galaxy NGC 4993 only 11 hours after the GW trigger (Coulter et al. 2017); this led to development of a new service[1] to facilitate follow-up observations of GW events. New computational techniques powerful enough to process TB/day rates of high-dimensional data with low latency will be important to *multi-messenger* astronomy in the LSST plus LIGO+, VIRGO, KAGRA, INDIGO era.

3. Increasing the Discovery Space

3.1 *Observing facilities that expand boundaries*

Any new observing facilities/missions for the next decade should significantly improve performance in some key metric (e.g., energy range, sensitivity, exposure time, angular resolution, higher dimensional data, rapid response), and be well characterized and calibrated, so to provide flexibility for new observing avenues. *Hubble*, *Spitzer* and *Chandra* provide examples in the discovery of Dark Energy, the detection of z=11 galaxies, and the nature of Dark Matter (Bullet Cluster), respectively. Beyond hardware capabilities these discoveries require: mission longevity, community driven science, high-quality data products in readily accessible, interoperable, archives and a well-supported user/observer community.

3.2 *Multi-wavelength and multi-messenger capabilities*

Many historical examples also demonstrate a strong synergy between different wavebands and messengers. Having contemporaneous access to the entire electromagnetic spectrum was vital to finding the first counterpart to a gravitational wave source, for example. This multi-wavelength coverage of the sky that we are currently enjoying needs to be preserved.

3.3 *Curated Data Archives and Powerful Data Analysis tools*

These new facilities will generate increasingly larger and complex multi-wavelength and multi-messenger data sets and catalogs. These data will need to be properly reduced and curated to fully enable their discovery potential. *Archives must provide both easy access to these data and (with the community) the means to exploit them*. These goals translate into:

(1) Ensure that any operational (old and new) facility/mission explicitly include in their scope the proper processing of software so to produce well documented and calibrated data products, as well as the capability for data recalibration and reprocessing.

(2) Organize these data products in well-maintained archives, following the International Virtual Observatory Alliance (IVOA)[2] standards, so to allow a basic level of access and *interoperability*, as well as *repurposing.* Much of this is already in place in the NASA archives, and they are collaborating in extending and evolving these capabilities to meet the demands of new data types and research methods through the 2020s. Data products should be replicable and reproducible, ranging from basic observation data to high-level aggregated data and catalogs.

(3) Ensure that data centers engage in the development and refinement of interoperability standards, via the well-established processes of the IVOA, and work with groups such as *Astropy*[3] to ensure support for these standards in present in community developed, open source software.

(4) *New facilities* (Sections 3.1, 3.2) *will demand a transformation in the way data are analyzed*. The early phases of this transformation are already underway (e.g., the use of *Python* as an

[1] https://ned.ipac.caltech.edu/gwf/

[2] The forum for the development of the interoperability standards used by major astronomy datacenters (http://www.ivoa.net)

[3] http://www.astropy.org/acknowledging.html

environment, cloud computing). But, resources must be made available for full development, which will demand remote Science Platforms[4] and Server-side analytics[5], implementation of complex fault-tolerant workflows, data mining and machine learning, and advanced visualization.

(5) Foster the development of *next generation* interoperable, user-friendly visual interfaces, data mining tools, the ability to construct and implement analysis workflows easily, both via visualization and scripting, and the ability to work with data both locally and remotely (current-generation well-know examples include TOPCAT, DS9 and CSCView).

(6) Support interdisciplinary research in astrostatistics and astroinformatics and the transfer of methods from the statistics, computer science, and machine learning communities, for development and application of innovative data analysis methods and algorithms.

(7) Ensure that facilities and archives participate in curation efforts and initiatives to link together datasets, related ancillary data (e.g., atomic and molecular databases), objects, and the literature.

Data are an important legacy of major astronomical facilities, and proper data maintenance will insure that new science will be produced for the future, even after the first crop of scientific papers and discoveries have been published. Statistics of data usage from the NASA archives demonstrate that archival data is used for new published scientific work several times (Fig. 1).

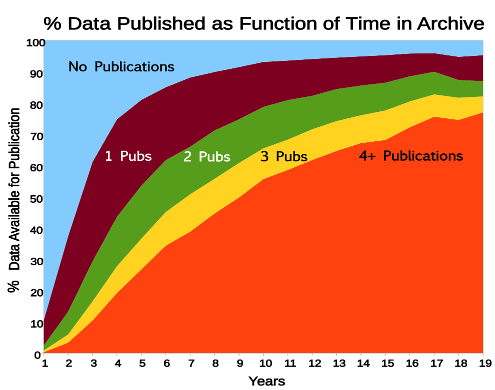

Figure 1. – Percentage of *Chandra* exposure time published versus years in the archive. The scientific use of archival *Chandra* data is increasing with time in the public archive. For example, 19 years from launch, ~75% of the observation have been published in more than 4 papers. A similar trend is observed for the HST data.

4. Conclusions

We propose <u>*exploration*</u> as the central question for the Decadal Committee's discussions. The history of astronomy shows that paradigm-changing discoveries were not driven by well-formulated scientific questions, based on the knowledge of the time. They were instead the result of the increase in discovery space fostered by new telescopes and instruments. An additional tool for increasing the discovery space is provided by the analysis and mining of the increasingly larger amount of archival data available to astronomers. We urge the Decadal Committee to **(1)** <u>*keep multi-wavelength and multi-messenger exploration center stage*</u> in their deliberations of new facilities, including consideration for flexible and well-calibrated modes of operation that could foster adaptation for use with new discovery space; and **(2)** <u>*recognize the importance of data and their stewardship, and computational services*</u>, as major elements of any new scientific development for the next decade. ***Revolutionary observing facilities, and the state-of-the-art astronomy archives needed to support these facilities, will open up the universe to new discovery.***

[4] See LSST Science Platform Design document https://ldm-542.lsst.io

[5] NASA Big Data Task Force (https://science.nasa.gov/science-committee/subcommittees/big-data-task-force)

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