Astro2020 Science White Paper

Increasing the Discovery Space in Astrophysics
The Exploration Question for Planetary Systems

Thematic Areas: Planetary Systems Star and Planet Formation

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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 planetary systems.

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 exoplanets and planet formation. 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 Planetary Systems and Planet Formation

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.

1) Pulsar planets - Aleksander Wolszczan (2000) discovered the first exoplanet and the first multiple exoplanet system (Konacki & Wolszczan 2003) in a place where nobody would ever have expected to find one: Orbiting a pulsar. This was done with Arecibo, a powerful instrument that was clearly not designed for the purpose of finding pulsar planets.

2) Hot Jupiters - 51 Peg b, the first exoplanet found orbiting a main sequence star, is a hot Jupiter. That is a type of planet that no theorist would have imagined could form. A week after its discovery, it was confirmed by looking at archival data from the Lick Observatory. This is a bit of a mixed discovery --- partly serendipitous, partly question-driven ---. Michael Mayor and Didier Queloz (1995), and other people were in fact trying to find exoplanets. But the thing they found was not at all what they expected.

3) Compact short period planet systems - The *Kepler* mission set out to find the frequency of Earth-like planets. Although it sort of failed in that mission because the momentum wheels broke, *Kepler* was an incredibly successful mission because it found a whole new population of planets that we did not know even existed. *The Galaxy is littered with compact planetary systems with orbital periods well inside the orbit of Mercury.* This again, is a mix of "question driven" and "exploration driven" discovery. *Kepler* was designed to answer one question, but its greatest contribution to the field was in answering a question that no one had asked.

4) Super-Earths and mini-Neptunes - The open search for planetary transits by the Kepler mission led to the discovery that the most common class of planet is one that does not exist in our solar system – one that has a size larger than Earth, but smaller than Neptune (2-10 Earth Radii) and typically periods > 3 days. The nature of these novel planets is ambiguous as they lie near the boundary between rocky planets and gas giants. These planets may have their atmospheres stripped by high energy particles from the host star (c.f. Fulton & Petigura 2018).

5) Atmospheric Haze – Heated and extended atmospheres have been detected around several Hot Jupiters and hot Neptunes. Photometry has suggested the existence of inhomogeneous Silicate-based cloud layers in several hot Neptune systems. Transmission spectroscopy has detected sodium and water vapor in the atmospheres of hot Jupiters, as well as *unpredicted hazes*, made of solid particles in an atmosphere that were formed by photochemistry.

6) HL Tau and its protoplanetary disk - HL Tau is a very young (10^5 years) T Tauri star surrounded by an equally young protoplanetary disk. Figure 1 shows an ALMA image of HL Tau. These observations were science verification taken by ALMA to test the long interferometric baselines. Nobody expected to see such substructure in a disk that is so young.

The image of HL Tau shows this very distinct ring structure and nobody's really sure of what it means. Recall that ALMA shows the location of the dust component of the disk. So the *dust* is in rings. Why? Could the black regions be gaps caused by planets? That is hard to believe given how young the system is and how many gaps there are. Maybe the dust is being accumulated inside pressure bumps in the gas that are caused by... something? Or perhaps there are no pressure bumps... perhaps the gaps are the signature of dust being converted into planetesimals... maybe. In any case, we still do not know what this image means, but we do know that HL Tau is not unique. ALMA has since found similar structures in many other protoplanetary disks (e.g., Andrews et al (2018); van der Marel et al. 2019), and there is now a great deal of effort in trying to understand what this all means.

HL Tau is again partly an example of question-driven and exploration-driven discovery. ALMA was intended to study protoplanetary disks. But nobody had expected such young protoplanetary disks to have this many rings. That discovery came as a by-product of the new capabilities provided by ALMA.

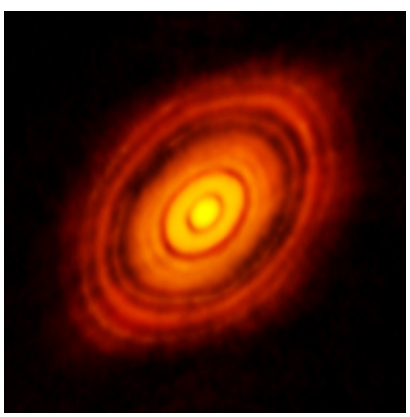

Figure 1.

ALMA (2015) image of the HL Tau disk

7) Protoplanetary disk ionization - For decades, astrophysical models of the Solar Nebula and (later) protoplanetary disks treated them as cold structures of gas and dust with no external effects other than gravitational attraction and blackbody heating from their host star. But in 1991, Balbus & Hawley (ApJ, 3000 citations) realized that only 10^{-12} fractional ionization of cold molecular material is sufficient to initiate the *magneto-rotational instability*, rapidly building a magnetic dynamo and induce MHD turbulence. This solved some problems (providing a source of viscosity needed for accretion, and mitigating Type I inward migration of Jovian protoplanets) but raised other problems (inhibiting dust settling needed to initiate planetesimal growth). Hundreds of theoretical studies relating to planet formation in turbulent disks emerged, but also unexpected interactions with observations. The *Chandra,* NASA's flagship X-ray observatory, was studying variable X-ray emission in thousands of pre-main sequence stars. These empirical studies showed that hard X-rays from protostellar magnetic reconnection flares can penetrate deep into the disks, and probably dominate the ionization of the planet forming region. Thus, a telescope designed to elucidate superheated disks around black holes is surprisingly addressing the astrophysics of cold circumstellar disks giving rise to planetary systems.

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)[1] 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*[2] 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 environment, cloud computing). But, resources must be made available for full development,

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

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

which will demand remote Science Platforms[3] and Server-side analytics[4], 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. 2).

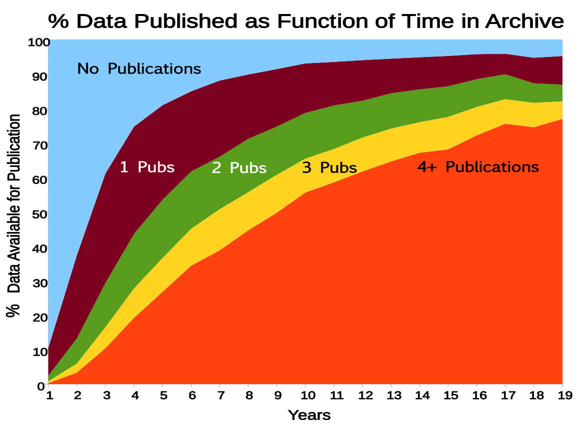

Figure 2. – Percentage of *Chandra* exposure time published versus years in the archive. The scientific use of archival *Chandra* data is increasing with time in the public archive. For example, 19 years from launch, ~75% of the observation have been published in more than 4 papers. A similar trend is 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.***

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

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

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