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# Editor's grand challenge in fundamental astronomy: Towards statistical accountability

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## 1 A "golden age" of opportunities

The field of astronomy, particularly observational astronomy, is in the midst of a golden age of opportunities. State-of-the-art observational facilities allow deeper, more accurate and more precise measurements of the fundamental physical properties governing the Universe on scales from stars and planetary systems to the cosmological horizon, across an ever-increasing range of wavelengths and frequencies. Multi-messenger data sets and dedicated astrometric and time-domain surveys at unprecedented scales—in terms of both spatial and temporal coverage, as well as spatial and spectral resolution—now offer the first opportunities to connect the local to the cosmological in an internally consistent fashion.

Systematics among data sets can finally be addressed conclusively by virtue of the statistically unprecedented surveys that have only recently become possible, a trend that is set to expand into the time domain in the near future at levels never seen before (e.g., the Vera Rubin Observatory/Legacy Survey of Space and Time; Ivezić et al., 2019). With systematic uncertainties smaller than ever before, complementary theoretical advances—supported by appropriate statistical analyses—should allow us the obtain an increasingly precise view of the Universe across many domains in Fundamental Astronomy, from solar physics to exoplanetary science, from extragalactic astrophysics to cosmology and even General Relativity (e.g., Klioner, 2008).

## 2 Making robust new discoveries

With a change of Specialty Chief Editor, opportunities are created for a refocus, or at least a renewed focus on particular areas of relevance. The scope of the *Fundamental Astronomy* section of *Frontiers in Astronomy and Space Sciences* is simultaneously narrowly defined and incredibly broad. Fundamental Astronomy is an essential branch of modern gravitational physics, which explores the fundamental structure of space and time (which may now no longer be fundamental in their own right; e.g., Proctor, 2022) by studying the dynamics of massive bodies and elementary particles, such as photons, in gravitational fields on time-scales from one orbital revolution to the Hubble time. It establishes basic theoretical principles for high-accuracy calculations and interpretation of various astronomical behaviours and phenomena observed in gravitationally bound systems. It also provides definitions and models that describe reference systems and frameworks used in astronomy and geodesy. Fundamental Astronomy pertains to physical information about celestial objects and investigations of physical laws using astrometry, celestial mechanics and space geodesy, including long-baseline radio and optical interferometry, laser and radio ranging, pulsar timing, Doppler tracking, space astrometry, atomic clocks and Global Positioning System, among other techniques.

However, none of these widely disparate fields stand a chance at making breakthrough discoveries without a proper, in-depth understanding of the uncertainties affecting their results—both observational and theoretical. Although many astrophysicists are convinced that their statistical approaches are beyond reproach, colleagues in the field of statistics often tend to disagree. Most astronomical efforts at statistical analysis do not go much beyond application of the normal distribution, perhaps skewed, Fourier transforms for temporal analysis, Kolmogorov–Smirnov tests, least-squares regression, chi-squared minimisation, or—heaven forbid—$p$-hacking (e.g., Feigelson and Babu, 2003).

Statistics as a field has an enormously rich pedigree, with applications across many areas of our daily lives. Borrowing from modelling approaches commonly used by, e.g., economic statisticians and econometrists, astrophysics research has in recent years seen increasingly sophisticated astrostatistics applications (e.g., Feigelson et al., 2021). And while I do not advocate a shift in the focus of the *Fundamental Astronomy* section to become a surrogate *Astrostatistics* section, here I extend a key challenge to my section's Editorial Board and our authors to pay careful attention to the proper use of statistical approaches and the honest reporting of the prevailing uncertainties.

As such, and given the significantly increased data sets that are now routinely becoming available in many areas of cutting-edge research pertaining to this field, the *Fundamental Astronomy* section will add an enhanced focus on applications of appropriate statistical tools, aiming to minimise validation of spurious results owing to unrecognised systematics. Careful and reproducible validation of the basic premises in all domains covered remains the bottom line.

Ultimately, therefore, this challenge is simultaneously an appeal to our community to redouble our efforts to understand and characterise the prevailing systematics across the wide gamut of subject areas covered by the section, while also considering—perhaps reconsidering—the calibrations underlying our interpretation of our observational and simulation results. With increasingly large data sets, combined with novel ground- and space-based observatories allowing us to explore phenomena that are inaccessible from a traditional optical and (near-)infrared perspective, now is indeed the time to reduce photometric, astrometric and spectrophotometric calibration uncertainties by up to orders of magnitude.

## 3 Cutting-edge developments

Among the most pressing current problems in Fundamental Astronomy are headline issues that require additional data to make new and ground-breaking discoveries, whereas others demand a major focus on modelling efforts in order to place tighter constraints on the fundamental parameters driving the prevailing physics.

Among the closest astrophysical objects to our home planet, the Sun and its physical drivers remain enigmatic. Centuries of observational records, dating back to at least 1,609, have allowed us to establish that the Sun is subject to an 11-year solar cycle (e.g., de Grijs and Kamath, 2021), associated with a global magnetic-field reversal, but its physical drivers remain as yet largely unknown. A major additional headline problem linked to our understanding of the Sun as a model for more distant solar-like stars is the thermodynamics of the solar corona's temperature inversion. If we do not fully understand the basic physics driving solar activity, how then can we interpret "solar-like" stellar activity at distances where details are at best marginal?

On much larger physical scales and tracing back to the origin of the Universe as a whole simmers a fundamental issue of great concern to cosmologists, the so-called "lithium problem" (e.g., Fields, 2011; Deal and Martins, 2021). Current Big Bang nucleosynthesis models provide an excellent description of the abundance of hydrogen and helium mere minutes after the Big Bang, but the amount of lithium, specifically the $^{7}$Li isotope, is underpredicted by factors of $\sim$3 by the most commonly adopted models. Do we need additional, more accurate data to resolve this fundamental problem, or are the calculations skewed by an unrecognised error? Does our current, state-of-the-art understanding of nuclear physics paint a complete picture of all nuclear reactions that should be included, or are we missing some?

Cosmological constraints continue to be tightened thanks to the dedicated efforts by many colleagues working across a wide range of subfields. Yet, the headline discrepancy in our best estimates of the Hubble parameter from local measurements compared with *Planck* data pertaining to the cosmic microwave background, now diverging by 5$\sigma$ (e.g., Riess et al., 2022), raises important questions about our understanding of the distance calibrations routinely applied to a wide range of distance indicators. Resolving the significant systematic uncertainties lingering in this field has emerged as one of the key issues of importance in present-day cosmology. Indeed, knowing the distance to an astrophysical object is key to understanding it: without an accurate distance, we do not know how bright it is, how large it is, or even (for great distances) when it existed (e.g., de Grijs, 2011).

On the largest scales, distances and redshifts are intricately related to one another, with various distance estimates also directly dependent on the curvature of the Universe, and hence on the nature of the reportedly ubiquitous dark matter and dark energy—neither of which are understood satisfactorily at the present time. Whereas the prevailing observations are routinely interpreted as suggesting the need for an invisible mass component to reconcile them with the predictions from Newtonian dynamics, post-Newtonian terms may be required to understand the Universe on the largest scales (e.g., Joyce et al., 2016)—an area often scoffed at by traditionalists, but might there be a kernel of truth in such approaches?

And do we really understand the nature of black holes? Originating from the Theory of General Relativity, black holes are now routinely thought to be lurking at the centres of most large galaxies. At least, state-of-the-art kinematic and dynamical measurements imply the need for supermassive objects coincident with galaxy nuclei. But are these the mathematical black holes predicted by the Theory of General Relativity, or are they instead eternally collapsing objects (Crawford and Tereno, 2002; Mitra, 2021), singularities in space where time is thought to end? Whereas the physics and mathematics tell us that we will never be able to peek inside a black hole's event horizon, in recent years we have been treated to the first images of the event horizons of the supermassive black holes in the centres of Messier 87 (Event Horizon Telescope Collaboration et al., 2019a; Event Horizon Telescope Collaboration et al., 2019b) and our own Milky Way Galaxy (Event Horizon Telescope Collaboration et al., 2022a; Event Horizon Telescope Collaboration et al., 2022b). The prospects for major breakthroughs in this field look bright, not least also because of exciting new developments produced by the current generation of gravitational-wave detectors (Bailes et al., 2021).

Much closer to home, at least mostly within our Galaxy, exoplanetary research is now on the verge of routinely detecting Earth-like planets, and so perhaps the next steps in that field may be dedicated studies of exoplanetary climate and surface conditions (e.g., Galuzzo et al., 2021) and the possible evidence of the presence of biomarkers. However, spectral degeneracies associated with different climate observables are currently one of the bottle necks that must be overcome to reach firm conclusions. This is where model builders will need to play a major role and drive novel developments.

Although this Editorial Challenge is necessarily limited in scope and length, here I have attempted to sketch a picture of some of the many opportunities that may be tackled and find a home in the pages of the *Fundamental Astronomy* section of *Frontiers in Astronomy and Space Sciences* following careful peer review. It is interesting to realise that the most pressing problems we have identified today are not too different in nature from those highlighted by Herbert Morgan (1937) in his January 1937 article in *Science*, titled "Some Problems in Fundamental Astronomy."

I am excited by the many prospects to make a major impact across the many subfields covered by the broad area of Fundamental Astronomy. I hope that you are too!

## Author contributions

The author confirms being the sole contributor of this work and has approved it for publication.

## Conflict of interest

The author declares that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

## Publisher's note



## References

Bailes, M., Berger, B. K., Brady, P. R., Branchesi, M., Danzmann, K., Evans, M., et al. (2021). Gravitational-wave physics and astronomy in the 2020s and 2030s. *Nat. Rev. Phys.* 3, 344–366. doi:10.1038/s42254-021-00303-8

Crawford, P., and Tereno, I. (2002). Generalized observers and velocity measurements in general relativity. *General Relativ. Gravit.* 34, 2075–2088. doi:10.1023/A:1021131401034

de Grijs, R. (2011). *An introduction to distance measurement in astronomy*. Chichester: Wiley.

de Grijs, R., and Kamath, D. (2021). Stellar chromospheric variability. *Universe* 7, 440. doi:10.3390/universe7110440

Deal, M., and Martins, C. J. A. P. (2021). Primordial nucleosynthesis with varying fundamental constants. Solutions to the lithium problem and the deuterium discrepancy. *Astron. Astrophys.* 653, A48. doi:10.1051/0004-6361/202140725

Event Horizon Telescope Collaboration, Akiyama, K., Alberdi, A., Alef, W., Asada, K., Azulay, R., et al. (2019a). First M87 Event Horizon Telescope results.

I. The shadow of the supermassive black hole. *Astrophysical J. Lett.* 875, L1. doi:10.3847/2041-8213/ab0ec7875L

Event Horizon Telescope Collaboration, Akiyama, K., Alberdi, A., Alef, W., Asada, K., Azulay, R., et al. (2019b). First M87 Event Horizon Telescope results. IV. Imaging the central supermassive black hole. *Astrophysical J. Lett.* 875, L4. doi:10.3847/2041-8213/ab0e85875L

Event Horizon Telescope Collaboration, Akiyama, K., Alberdi, A., Alef, W., Algaba, J. C., Anantua, R., et al. (2022a). First Sagittarius A* Event Horizon Telescope results. I. The shadow of the supermassive black hole in the center of the Milky Way. *Astrophysical J. Lett.* 930. doi:10.3847/2041-8213/ac6674930L.12E

Event Horizon Telescope Collaboration, Akiyama, K., Alberdi, A., Alef, W., Algaba, J. C., Anantua, R., et al. (2022b). First Sagittarius A* Event Horizon Telescope results. III. Imaging of the Galactic Center supermassive black hole. *Astrophysical J. Lett.* 930, L14. doi:10.3847/2041-8213/ac6429930L.14E

Feigelson, E. D., and Babu, G. J. (2003). *Statistical challenges of astronomy*. New York, NY: Springer.

Feigelson, E. D., de Souza, R. S., Ishida, E. E. O., and Jogesh Babu, G. (2021). Twenty-first-century statistical and computational challenges in astrophysics. *Annu. Rev. Stat. Appl.* 8, 493–517. doi:10.1146/annurev-statistics-042720-112045

Fields, B. D. (2011). The primordial lithium problem. *Annu. Rev. Nucl. Part. Sci.* 61, 47–68. doi:10.1146/annurev-nucl-102010-130445

Galuzzo, D., Cagnazzo, C., Berrilli, F., Fierli, F., and Giovannelli, L. (2021). Three-dimensional climate simulations for the detectability of Proxima Centauri b. *Astrophys. J.* 909, 191. doi:10.3847/1538-4357/abdeb4

Ivezić, Ž., Kahn, S. M., Tyson, J. A., Abel, B., Acosta, E., Allsman, R., et al. (2019). Lsst: From science drivers to reference design and anticipated data products. *Astrophys. J.* 873, 111. doi:10.3847/1538-4357/aaf73c

Joyce, A., Lombriser, L., and Schmidt, F. (2016). Dark energy versus modified gravity. *Annu. Rev. Nucl. Part. Sci.* 66, 95–122. doi:10.1146/annurev-nucl-102115-044553

Klioner, S. A. (2008). "Relativity in fundamental astronomy: Solved and unsolved problems," in Proceedings of the Journées Systèmes de Référence Spatio-temporels 2007. Editor N. Capitaine, 127.

Mitra, A. (2021). *The rise and fall of the black hole paradigm*. Sydney: Pan Macmillan.

Morgan, H. R. (1937). Some problems in fundamental astronomy. *Science* 85, 1–9. doi:10.1126/science.85.2192.1

Proctor, A. C. (2022). *On time, causality, and the block Universe*. New York, NY: Clink Street Publishing.

Riess, A. G., Yuan, W., Macri, L. M., Scolnic, D., Brout, D., Casertano, S., et al. (2022). A comprehensive measurement of the local value of the Hubble constant with 1 km $s^{-1}$ $Mpc^{-1}$ uncertainty from the Hubble Space Telescope and the SH0ES team. *Astrophys. J. Lett.* 934, L7. doi:10.3847/2041-8213/ac5c5b