Chapter 1
Introduction

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Abstract This volume is the first edited collection of philosophy of astrophysics. In this introductory chapter, we provide a brief history of the rise of philosophy of astrophysics as a distinct subdiscipline in philosophy of science, brief summaries of the chapters in the volume and their interrelated themes, and a few suggestions for further work.

The volume you have before you is the first edited collection specifically devoted to philosophy of astrophysics. Our primary aims in producing this volume have been to gather contemporary research in philosophy of astrophysics together in one place as both a reference resource for scholars already working in this subdiscipline and as an introduction to curious newcomers. Several contributions in this volume will also likely be of interest to philosophers working on topics such as idealization, validation, and analogy, which extend well beyond the specificity of philosophy of astrophysics. This introduction provides some background on the rise of philosophy of astrophysics as a distinct subject area, brief summaries of the contributions, and closes with a few suggestions for future work.

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1.1 Philosophy of Astrophysics Until Today

Astronomy, the observational science of the positions, motions and properties of celestial bodies, has a long and storied history, with roots going back even to prehistoric times.[1] Astrophysics ‘proper’, the scientific discipline that applies the laws of physics and chemistry to provide a dynamical explanation of these astronomical observations, originated in the unification of celestial and terrestrial physics from the Scientific Revolution, but found its proper start with the development of spectroscopy in the nineteenth century. Already by the early twentieth century, a relatively detailed theory of stellar evolution and stellar structure had been developed. Today, astrophysics is still progressing with leaps and bounds. For instance, in the 30 years since the first exoplanet discovery in 1992, over 5000 have been identified. LIGO detected its first gravitational wave signal in 2015, but by 2020 the collaboration was reporting candidate events at a rate of more than one per week (Abbott et al. 2021). With the expected launch of more advanced experiments like LISA, Euclid and the recently launched James Webb Space Telescope, as well as the development of better simulations, it is only to be expected that this process will continue.

Analytic philosophers of science have started to show interest in astrophysics since the 1980s, but philosophy of astrophysics has only properly come into maturity in the last decade or so. Indeed, Cameron Yetman’s complete overview of all papers and books (in English) in philosophy of astrophysics (included at the end of this volume) lists only 87 entries, three quarters of which were published since 2010. Although this introduction won’t go through every single one of these entries, it is worthwhile to review some of the history of the field to further explain why now is an especially salient time for an edited volume in philosophy of astrophysics.

Arguably the first philosophical writing in analytic philosophy of astrophysics was a series of remarks by Ian Hacking (1982, 1983, 1989). His was a negative take on the discipline. Hacking first observed a lack of experiments in astrophysics,[2] which led him to a negative conclusion about entity realism about astronomical objects (or, at least, astronomical objects not observable with the naked eye, like black holes and gravitational lenses). But the 1989 paper went much further: it claimed that the methodology of astronomy and astrophysics is merely one of saving the phenomena, and that, because of this methodology, “astronomy is not a natural science at all” (1989, 577).

A significant part of philosophy of astrophysics has been influenced by or directly responds to Hacking’s initial dismissal. The first, most direct, and broadest

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[1] See e.g. (North 2008) for a detailed history. Chanda Prescod-Weinstein’s reading list on decolonizing science (available here: https://medium.com/@chanda/decolonising-science-reading-list-339fb773d51f) is an excellent resource, providing important corrections to a common western-centric historical narrative.

[2] This is most clearly summarized by the famous line: “galactic experimentation is science fiction, while extra-galactic experimentation is a bad joke” (Hacking 1989, 559).

response came from Shapere (1993). Shapere both defended the scientific status of astronomy and astrophysics and argued against the coherence of Hacking's entity realism more generally. But parts of the debate also percolate through in discussions about astronomy as a historical science (Anderl 2016; Cleland 2002), realism and astrophysics (Leconte-Chevillard 2021; Martens 2022), and the nature of direct or indirect observations in astrophysics (Elder 2020; Sandell 2010).

Nonetheless, the initial controversy about Hacking's gambit did not spur the development of philosophy of astrophysics as its own sub-field in philosophy of science. During the 1990s and 2000s, any philosophy of science engaging with astrophysics tended to remain limited to a few individual researchers using case-studies from astrophysics to engage with ongoing debates in philosophy of science. While such engagement is important—one goal of the current volume is to show how astrophysics presents a unique perspective on many debates in philosophy of science—these papers rarely explicated the unique philosophical opportunities posed by astrophysics.

Even if those papers do not make the unique philosophical interest of astrophysics explicit, they do so implicitly. For instance, Bailer-Jones (2000) uses the case of extragalactic radio sources to illustrate challenges arising in modeling novel phenomena, something especially prevalent in astrophysics, where novel physics (from types of supernovae to dark matter) is lurking around every corner. Cleland (2002) includes astrophysics as one example of a historical science in her discussion of the methodological differences between historical and experimental sciences. Insofar as astrophysics is reconstructing the past, there is an important contrast with areas like paleontology or evolutionary biology: there are strict constraints from established theories of physics. Ruphy (2010) shows how stellar kinds bear onto the natural kinds debate. And, finally, Salmon (1998) highlights the challenge of distinguishing between pseudo-processes and causal processes in astrophysics.[3]

Thus, a coherent body of work focusing specifically on philosophical questions arising in astrophysics remained wanting throughout the 1990s and 2000s. But the first seeds were already there. Aside from the aforementioned papers, it is also worth mentioning Bill Vanderburgh (2003, 2005) laying the groundwork for philosophy of dark matter. And in science and technology studies, the 2000s see an ongoing discussion about, e.g. the categorization of moons and planets (Messeri 2009; Metzger et al. 2022), and later on about the creation of telescope images (English 2017; Greenberg 2016) and of simulations (Sundberg 2010, 2012).

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[3] The chapter is a hidden gem towards the end of Salmon's 1998 book on causation. It includes a full record of Salmon's correspondence with astrophysicists about a controversy about size measurements, as well as great personal anecdotes like the following: "In order to display [the shape of a spiral galaxy], I looked through our home collection of old LP records and serendipitously came upon "Cosmo's Factory" by the Creedence Clearwater Revival, a happy discovery given that we are interested in various types of engines in the cosmos, a clearing of the waters muddied by invalid arguments, and in a revival of credence in theories or models of such engines" (377–378).

From 2010 onwards, the philosophical literature shows a significant shift. Certain central themes in philosophy of astrophysics ‘proper’ started to crystallize out, this time in tandem with, but no longer solely in service of ongoing debates in philosophy of science. The annotated bibliography at the end of this volume gives a comprehensive overview divided into seven categories. Here, we close the historical overview by highlighting three themes that have garnered most attention since 2010—three themes that are also reflected by the contributions in this volume.

First, there is the question of how astrophysicists come to gather empirical evidence. No current philosopher of astrophysics would want to lapse into Hacking-style skepticism about the scientific status of astrophysics. But the question still stands of how astrophysical models are constrained by what Quine simply referred to as the ‘tribunal of experience’. This becomes especially pressing when scientists are aiming to detect signals of novel physics that are buried in noise, like in the case of gravitational wave astronomy. A second theme is the epistemology of computer simulations. Astrophysicists use computer simulations to draw out empirical consequences of theoretical models, or to extend the epistemic reach of observations. But how is the reliability of simulations themselves established? Third, there is now quite an extensive literature on philosophy of black hole astrophysics. The aforementioned epistemology of gravitational wave astrophysics fits here, but also the recent debate about analogue gravity experiments.

From this brief historical overview, it is clear that philosophy of astrophysics has finally come to fruition. The contributions in this volume, which we summarize in the next section, represent how broad the discussion has become.

1.2 Philosophy of Astrophysics in This Volume

The contributions to this volume expand upon predominant themes of the extant philosophy of astrophysics literature. The book opens with a contribution by **Boyd**, which addresses the provocative challenge posed by Hacking mentioned above. While Hacking denies the empirical status of astrophysics due to the lack of experiments, Boyd attentively considers the field of laboratory astrophysics experimentation, which is often carried out by appealing to similarity arguments. In particular, she illustrates the case of laboratory supernova research carried out at the National Ignition Facility, which includes experiments studying the Rayleigh-Taylor hydrodynamic instability and based on the hydrodynamic similarity between terrestrial and celestial physics. While her conclusion cautiously warns against the purported epistemic significance of the particular experiment that is the subject of her case study, she also suggests that the division between experimental and non-experimental sciences is of little significance when evaluating the empirical status of astrophysics and, in general, any scientific discipline. Rather, according to her, attending to the empirical data and focusing on their causal chain can better illuminate the external validity of astrophysics research.

While Boyd convincingly underplays the significance of Hacking's challenge, she demonstrates a way of assessing the epistemic authority of astrophysics that nests complex epistemic challenges, which are beautifully addressed by the other contributions of this volume. In particular, the attention to how data is collected and to the enriched empirical evidence that they provide spurs questions on the reliability, validity and objective value of data, and on the connection between the results of astrophysical observations and theory.

Elder's and Patton's contributions richly exemplify the problem of data theory-ladenness and the hybridization of theoretical and empirical reasoning. **Elder**'s paper discusses both the vices and virtues of interdependence in theory testing by illustrating the case of the LIGO-Virgo experiments methods. Thanks to their very first direct detection of gravitational waves, the LIGO-Virgo experiments have opened the path not only for a successful observation of the universe, but also for a rigorous test of General Relativity (GR). The concern, however, is that the theory-ladenness of the LIGO-Virgo methods leads to a potentially vicious epistemic circularity, where GR assumptions and models may serve to interpret data that are actually inconsistent with GR as consistent. While the author clearly articulates the complex layers of theory-ladenness involved in the LIGO-Virgo experiments, and the threats of the vicious circularity involved, her conclusion is optimistic. Elder shows how the problem of circularity can be satisfactorily mitigated by leveraging improvements in modeling, simulation, or observation in one domain to place constraints in another. **Patton**'s contribution pursues a similar line of thought. She argues against the direct empiricist perspective according to which data are treated as windows on the world and as reflections of reality, by illustrating the case of population synthesis methods, which employ theories and models in analyzing data and in simulations. Stellar evolution theory is the foundation of population synthesis, and models recruit theoretical and empirical stellar libraries to generate simulations. The progressive and stunning observational development and the obtainment of higher-resolution and more precise empirical data are accompanied with a more numerous and more sophisticated theoretical and modeling resources. In particular, Patton shows that the stellar population synthesis methods not only use theories and models to interpret and analyze the data, but also necessarily need them to measure physical parameters: the physical variables that are the target of population synthesis cannot be even measured without employing significant theoretical resources.

The contribution by **Martens and King** examines another important problem concerning data, which is a case of underdetermination of data by two theories that are not perfectly empirically equivalent and are even not perfectly empirically adequate. The case presented is on dark matter and modified gravity. While the ΛCDM-model is still affected by small scale problems, modified gravity is unable to provide an accurate description of galaxy clusters and cosmological observables. Thus, they argue that in this case, the presumption of solving the underdetermination by an attentive examination of the empirical data is bound to fail. Martens and King provide a thorough theoretical discussion of both theories with regard to two theoretical virtues, which are unificatory power and simplicity.

Gueguen's contribution also deals with the problem of discord between different programs, in this case, of the Hubble constant controversy, which has been sometimes labeled as a crisis. Her approach is not theoretical but follows Boyd's suggestion of attending to the causal chain of empirical data and how they are collected: it provides an attentive analysis of how astrophysicists check for the errors affecting their measurements. Gueguen's contribution on the Hubble constant controversy showcases the intricate process of cross-checking different results in order to detect unknown systematic errors by the use of systematic replications and robustness analysis. While one well-trodden path would be to use robustness arguments to take the discrepancy of results of the Hubble constant value recently obtained as a clear sign of a crisis, after an attentive analysis of how the measurements are carried out, Gueguen warns against a precipitous evaluation of this case as a 'crisis' and endorses a more cautious approach that highlights the need for a better assessment of the presence of systematic errors. In this sense, her conclusion challenges those who have claimed there is a crisis in astrophysics: while the failure of systematic replications offered by the Tip of the Red Giant Branch and the Cepheids' teams and the consequent lack of robustness of results inform us of how their measurements can be further improved, it would be epistemically unjustified to use it to support a crisis of astrophysics.

While epistemic challenges are ubiquitous in astrophysics research, the extensive use of simulations is often regarded as a source of concerns that is more worrying than others. Indeed, simulations are often regarded as unsatisfactory to act as epistemic authorities in an empirical field, as they lack one of the most important components of experimental research, which is manipulation of the target system. In her contribution, **Abelson** challenges the common lore that simulations can play the role of experiments. Her thesis, however, is cautious. While she remains reluctant to regard simulations as experiments, she shows how a certain kind of astrophysical simulation can be regarded as conceptual experiments. These are dynamical simulations of temporal systems, which instantiate a significant amount of empirical temporal data and achieve a higher level of representational adequacy.

The contribution by **Kadowaki** concerns the epistemic justification of simulation as well. While a common practice to check for the reliability and trustworthiness of simulation would require the separation of the numerical/computational aspects of simulation from the relation of the simulation to its real-world target system, and separate the process of Verification from the process of Validation, the author argues that this is not epistemically advisable. Kadowaki supports his claim with a survey of the verification tests used in selected magnetohydrodynamics simulations. This case study shows that verification tests are not mere tests of numerical fidelity, as they also involve an exploration of the domain of possible real-world systems and of the space of simulation code types.

Another contribution that deals with the problem of the epistemic standing of simulations is the chapter by **Meskhidze**. She discusses code comparison, which is a method to check for the reliability and trustworthiness of computer simulations, and which has been criticized for relying on shaky grounds, as it is arguably not possible to achieve a good balance between difference and similarity to allow for a fair and informative comparison. Meskhidze presents a project she joined, which investigated two different implementations of self-interactions amongst dark matter particles in two computer simulation codes. In this case, the code comparison was epistemically informative, as the simulation outputs were diverse enough for an informative comparison and yet still comparable. Her conclusion is both optimistic and cautious: it shows that code comparisons, in cases where it is conducted as a part of eliminative reasoning, can be used to increase our confidence in computer simulations.

Along the same lines, **Gallagher and Smeenk** evaluate the reliability of simulation in spite of the challenge of 'uncomputed' alternatives, by examining the case of quasar formation. The problem of uncomputed alternatives is a type of selection effect that results from neglecting certain physically plausible scenarios because they are computationally intractable. In the case of quasar formation, some plausible explanations for the triggering of quasar activity have not been explored using simulations, and therefore have not been subjected to detailed observational evaluation, because of their computational intractability.

Another reason why the epistemic authority of simulations has been regarded with suspicion is its extensive use of idealization. **Jacquart and Arcadia**'s contribution deals with the problem of idealization. Their case study of Collisional Ring Galaxies simulations provides a perfect platform to analyze the nature of different kinds of idealization, their epistemic roles, and to discuss the delicate and sophisticated process of de-idealization involved in simulations. As their contribution shows, this process may involve different strategies, ranging from 're-composing' by adding back in features into a model that were at one point idealized, to 'reformulating', 'concretizing', and 'situating'. The authors highlight that these de-idealizations cannot be done as a simple reversal, and that they are processed according to the various aims and goals of the astrophysicist team.

The problem of idealization is very much connected to the problem of the extensive use of 'fictions' in models. **Suárez**' contribution summarizes the recent development of the field of asteroseismology and discusses its use of fictional posits, which are employed as effective means in allowing modellers to generate expedient predictions for observable quantities. While fictional assumptions have no further cognitive value beyond the convenience of their expediency, some of them have turned out to be just false idealizations. New asteroseismical methods, indeed, have produced knowledge regarding the energy transfer mechanisms inside a multitude of stars of different types, and this has shown that the equilibrium, spherical symmetry, and uniform composition assumptions do not operate as fictions, but are rather better understood as false idealizations.

The challenges that astrophysics has to face not only arise from the scientific tools used in their method, but also because of the nature of the objects of its investigation. This volume has dedicated one whole section to black holes, as the difficulties that hinder empirical access to black holes have encouraged the development of new epistemic techniques. These techniques range from indirect observation by the observation of their interaction with ordinary matter to analogical reasoning. **Mathie**'s chapter explores two uses of analogical reasoning regarding black holes, and the connections between them. On one hand, black hole thermodynamics relies on an analogical relationship between radiation from astrophysical black holes and radiation from ordinary thermodynamic systems. On the other hand, analog gravity experiments rely on arguments connecting analog systems displaying analog event horizons (in water, for example) to astrophysical black holes. Mathie argues that while physicists have generally been far more comfortable accepting the validity of black hole thermodynamics than analog gravity experiments, the analogical argument underpinning the former relies on input from the latter. In particular, black hole thermodynamics relies on the existence of astrophysical Hawking radiation, the evidence for which is only indirectly provided by the (to some, dubious) analog gravity experiments. Mathie considers, and ultimately rejects several strategies for avoiding this dependence.

Our final chapters by **Doboszewski and Lehmkuhl,** on the one hand, and by **Allzén** on the other hand, offer a complete overview of the epistemic challenges due to the nature of black holes and discuss several arguments for why our epistemic position with regards to black holes is problematic. Among other problems, they discuss that our epistemic access to black holes is not direct but indirect, and that black holes fail to be experimentally manipulable in a way that makes them deserving of a realist attitude, following not only Hacking's entity realism, but, as the paper by Allzén points out, also Cartwright's and Chakravartty's realist views. While Doboszewski and Lehmkuhl argue that all arguments supporting a failure of scientific realism are not convincing, Allzén's paper accepts that entity realism, as it stands, is not compatible with a realist attitude towards black holes. However, instead of supporting an anti-realist conclusion, the author seems to encourage a radical revisitation of our traditional realist criteria, according to the contemporary epistemic practices of astrophysics.

Following the contributed chapters, you will find a short essay titled "Reflections by a Theoretical Astrophysicist", written by our co-editor Kevin **Heng** in response to the contributions included in this volume. Heng's essay provides valuable insights for philosophers of science working in philosophy of astrophysics and more general topics such as modeling and simulation. He contrasts the practices and heuristics of working scientists, which are rarely explicitly mentioned in science publications, with the seemingly high standards of philosophers. Heng also notes several issues to which philosophers may wish to pay more attention, such as the inescapable influence of discretization in computer simulations and the unsolved problem of turbulence.

Taken together, we hope that the elements of this volume spark the further acceleration of valuable work in philosophy of astrophysics. From our vantage point, there are many fascinating avenues for future work. The ongoing engagement of philosophers with the Event Horizon Telescope is sure to produce additional illuminating scholarship on the relationships between theories, models, and empirical data, as well as the nature of astrophysical black holes. Exciting forays into philosophy of astrochemistry are currently underway. The domain of exoplanet research and the connections between planetary astrophysics, atmospheric, and climate science remain largely to be explored. Further case studies on the methodology and epistemology of laboratory astrophysics research, such as the formation of protoplanetary disks from low pressure dust, would undoubtedly enrich our understanding of the epistemology of experiment. While philosophers of astrophysics have investigated simulations of galaxies and galaxy clusters, and models of stars, the advanced stellar structure simulations have yet to receive due attention. Nurturing interdisciplinary collaborations between astrophysicists and philosophers will surely surface even further unforeseen questions and research topics and help strike the appropriate balance between fidelity to scientific practice and philosophical interest. Whatever directions the field ultimately takes, stars, simulations, and the struggle to determine what is out there will undoubtedly continue to inspire philosophical scholarship for many years to come.

References

Abbott, R., et al. 2021. GWTC-2: Compact Binary Coalescences Observed by LIGO and Virgo During the First Half of the Third Observing Run. *Physical Review X* 11 (2): 21053. https://doi.org/10.1103/PhysRevX.11.021053.

Anderl, Sibylle. 2016. Astronomy and Astrophysics in the Philosophy of Science. In *The Oxford Handbook of Philosophy of Science*. Oxford: Oxford University Press.

Bailer-Jones, Daniela M. 2000. Modelling Extended Extragalactic Radio Sources. *Studies in History and Philosophy of Science Part B – Studies in History and Philosophy of Modern Physics* 31 (1): 49–74.

Cleland, Carol E. 2002. Methodological and Epistemic Differences Between Historical Science and Experimental Science*. *Philosophy of Science* 69 (3): 447–451.

Elder, Jamee. 2020. *The Epistemology of Gravitational-Wave Astrophysics*. University of Notre Dame. https://curate.nd.edu/show/3f462517k8t.

English, Jayanne. 2017. Canvas and Cosmos: Visual Art Techniques Applied to Astronomy Data. *International Journal of Modern Physics D* 26 (4): 1730010.

Greenberg, Joshua M. 2016. Creating the "Pillars": Multiple Meanings of a Hubble Image. *Public Understanding of Science* 13 (1): 83–95.

Hacking, Ian. 1982. Experimentation and Scientific Realism. *Philosophical Topics* 13 (1): 71–87.

———. 1983. *Representing and Intervening*. Cambridge: Cambridge University Press.

———. 1989. Extragalactic Reality: The Case of Gravitational Lensing. *Philosophy of Science* 56 (4): 555–581.

Leconte-Chevillard, Gauvain. 2021. Experimentation in the Cosmic Laboratory. *Studies in History and Philosophy of Science* 90 (September): 265–274. https://doi.org/10.1016/j.shpsa.2021.10.005.

Martens, Niels C.M. 2022. Dark Matter Realism. *Foundations of Physics* 52 (1): 1–19. https://doi.org/10.1007/s10701-021-00524-y.

Messeri, Lisa R. 2009. The Problem with Pluto: Conflicting Cosmologies and the Classification of Planets. *Social Studies of Science* 40 (2): 187–214.

Metzger, Philip T., et al. 2022. Moons Are Planets: Scientific Usefulness versus Cultural Teleology in the Taxonomy of Planetary Science. *Icarus* 374: 114768. https://doi.org/10.1016/j.icarus.2021.114768.

North, John. 2008. *Cosmos: An Illustrated History of Astronomy and Cosmology*. Chicago: University of Chicago Press.

Ruphy, Stéphanie. 2010. Are Stellar Kinds Natural Kinds? A Challenging Newcomer in the Monism/Pluralism and Realism/Antirealism Debates. *Philosophy of Science* 77 (5): 1109–1120. https://doi.org/10.1086/656544.

Salmon, Wesley C. 1998. Quasars, Causality and Geometry: A Scientific Controversy That Did Not Occur. In *Causality and Explanation*, 369–384. Oxford: Oxford University Press.

Sandell, Michelle. 2010. Astronomy and Experimentation. *Techne* 14 (3): 252–269.

Shapere, Dudley. 1993. Astronomy and Antirealism. *Philosophy of Science* 60 (1): 134–150.

Sundberg, Mikaela. 2010. Cultures of Simulations vs. Cultures of Calculations? The Development of Simulation Practices in Meteorology and Astrophysics. *Studies in History and Philosophy of Science Part B – Studies in History and Philosophy of Modern Physics* 41 (3): 273–281. https://doi.org/10.1016/j.shpsb.2010.07.004.

———. 2012. Creating Convincing Simulations in Astrophysics. *Science, Technology & Human Values* 37 (1): 64–87.

Vanderburgh, William L. 2003. The Dark Matter Double Bind: Astrophysical Aspects of the Evidential Warrant for General Relativity. *Philosophy of Science* 70 (4): 812–832.

———. 2005. The Methodological Value of Coincidences: Further Remarks on Dark Matter and the Astrophysical Warrant for General Relativity. *Philosophy of Science* 72 (5): 1324–1335.