Institute of Astronomy
University of Cambridge

Natural Sciences Tripos
Part II Astrophysics

2023-24

Titles:

Unravelling the Nature of Dark Matter

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Essay Description

The existence of dark matter, which constitutes 85% of the matter density and 26% of the total energy density, is clearly demonstrated by cosmological observations of the Universe. And yet, very little is known about the nature of dark matter. The observations support the 'cold dark matter' (CDM) paradigm, in which the dark matter is a heavy particle, with little to no interactions through fundamental forces other than gravity. The cosmological and astrophysical observations of dark matter's gravitational interaction currently provide the only robust evidence of dark matter. These observations typically rely on characterising the distribution of matter in the Universe. The matter distribution in the CDM paradigm predicts complex structures ranging from large to small scales. The amount of structure is characterised by its statistical properties, and a defining trait of the CDM is that the amount of structures grows towards smaller and smaller scales.

A dark matter particle that is lighter than the standard CDM paradigm predicts imprints a suppression of structure in the matter distribution. The exact scale where this happens is most often linked to the mass of the dark matter particle, although the nature of this imprint can vary in different dark matter models. Nevertheless, empirical evidence for suppression of structure on small scales would be indicative of a possible paradigm shift away from the CDM model. Current and upcoming observational facilities are aimed at tackling these important questions through a wide range of methods. One of the main difficulties of robustly assessing the amount of structure on small scales is that 15% of the matter density, the ordinary matter consisting of hydrogen and helium, can also reduce the amount of structure on small scales. This ranges from pressure of the matter to more complex effects related to the formation of galaxies.

In this essay you should discuss different methods that aim to measure the suppression of structure on small scales and investigate some of the physical dark matter models that seek to explain the suppression of structure.

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Earth's Oxygenation History - One Key to Unlocking Exoplanetary Habitability

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Essay Description

The Earth's oxygenation history is a complex chain of events occurring over billions of years. The atmosphere has been shaped by both biological and geological transformations, with life evolving alongside these changes. During the Archean geological eon, Earth's atmosphere had negligible atmospheric concentrations of oxygen, before the photosynthetic activity of cyanobacteria combined with hydrogen escape, gave rise to the Great Oxidation Event. This occurred approximately 2.4 billion years ago and marked the start of the Proterozoic geological eon. Following this milestone, the Earth endured a protracted period known as the "Boring Billion," characterised by relatively stable and warm geological conditions. The Neoproterozoic Oxygenation Event, roughly 850 to 540 million years ago, ushered in another significant rise in oxygen levels. This coincided with the emergence and diversification of complex multicellular life forms and was followed by the Cambrian explosion, which witnessed the rapid proliferation of animal phyla.

When assessing the habitability of Earth-like exoplanets, it is sensible to turn to Earth's own history as a benchmark. How the oxygenation timeline correlates with the emergence and sustenance of complex life is uncertain. However, the presence of atmospheric oxygen on a planetary scale is crucial in determining habitability, as it gives rise to the ozone layer, which blocks harmful ultraviolet radiation from reaching the surface. Earth's journey from an anoxic environment to one abundant in oxygen provides valuable insights into the interplay between geological processes, atmospheric composition, and the evolution of life, serving as a reference point for evaluating the potential habitability of distant exoplanets. When future observations of Earth-like exoplanets are made, how astronomers interpret the observed transmission spectra and direct-imaging spectra will be key to determining if any worlds are habitable, and indeed, inhabited.

This essay should summarise the current state of knowledge regarding Earth’s oxygenated history and highlight the major events that transformed the biosphere. It should discuss the significance of Earth's oxygenation history as a foundation for discerning the conditions necessary for life to flourish on distant worlds. Additionally, it should explore various observational techniques employed by astronomers to identify the presence of oxygen and other potential biosignatures in the atmospheres of terrestrial exoplanets, ultimately commenting on the reliability of any future conclusions that may be reached regarding the possible presence of extraterrestrial life.

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- Meadows et al., 2018, Exoplanet biosignatures: understanding oxygen as a biosignature in the context of its environment, Astrobiology, 18(6), 630 https://www.liebertpub.com/doi/full/10.1089/ast.2017.1727
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Stellar contamination and mitigation in exoplanetary science

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Essay Description

Exoplanetology is an exciting new area of astrophysics that places our Solar system in the context of other exoplanetary systems. Although tremendous progress has been made in the last decade, stellar activity is a hindrance in both planet detection and atmospheric study. Stellar activity is the result of dynamically evolving magnetic fields produced in the stellar interior that are responsible, e.g., for the presence of stellar spots, chromospheric heating, and flares. Stellar activity produces astrophysical noise signals of different amplitudes and timescales that can hamper both detection and lead to spurious atmospheric species.

Debates around exoplanet detections continue to flourish due to confusion between the radial velocity signals induced by stellar activity or exoplanets. Signals intrinsic to the star give rise to radial velocity variability occurring over a wide range of time scales (Kjeldsen et al. 1995, Bouchy et al. 2002). The stellar activity signals can hinder detections by completely drowning out and even mimicking the radial velocity signals of genuine exoplanets (Saar & Donahue 1997, Queloz et al. 2001).

Exoplanet atmospheric observations are affected by the variations in the spectrum of the star on the timescales of the planetary transit (Agol et al. 2010, Sing et al. 2011). For instance, the spot distribution on the surface of the star can modify the transit depth. An unocculted spot can underestimate the planet-to-star radius by 10% in visible wavelengths (Oshagh et al. 2014). Unocculted spots can also lead to contamination and enable spurious detection of atmospheric species (Barstow et al. 2015).

The stellar activity noise is either modelled by employing the empirical proxies from activity indicators or by numerical simulation of the active region (Haywood et al. 2014, Rajpaul et al. 2015). This essay should review stellar contamination and explore the various mitigation techniques for exoplanet detection and their atmospheric observations.

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The rise of `gargantuan' black holes in the early Universe

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Essay Description

High-redshift surveys have so far discovered over a hundred quasars above redshift of six (for recent examples see, e.g., Mortlock et al., 2011, Banados et al., 2018). This number will likely increase significantly in the coming years, due to ongoing and planned deep, wide-field surveys, such as eROSITA in X-rays, the Vera Rubin Observatory's Legacy Survey of Space and Time (LSST) at optical wavelengths as well as Euclid in infrared. Such observations will also push these discoveries to lower luminosities too, giving a more complete picture of the build-up of the black hole population in the early Universe. In fact, as discussed in Inayoshi et al. (2020), it could even be possible to detect 105 solar-mass black holes accreting at the Eddington rate at redshift z = 10 with mega second exposures from NIRCam on JWST or from the proposed Lynx X-ray telescope. Excitingly, these very high-redshift black holes have started to be detected with JWST already (Maiolino et al., 2023a, Maiolino et al., 2023b, Matthee et al., 2023).

Focusing on the most extreme examples, supermassive black holes exceeding one billion solar masses have been detected above z = 7, challenging theoretical models of the growth of such objects (see, e.g., Wang et al., 2021). The current record holder in terms of luminosity, and hence black hole mass (assuming Eddington-based arguments) is SDSS J010013.02+ 280225.8, with an inferred mass exceeding 1010 solar masses at z = 6.3 (Wu et al., 2015). While there have been a number of theoretical studies of these objects (see, e.g., Sijacki et al., 2009, Costa et al., 2014, Zhu et al., 2022, Bennett et al., 2023), these simulations still struggle to form some of the most massive observed black holes at z > 6.

The aim of this essay is to review the current state of this research topic, both observational and theoretical, covering the following key points.

1. Why is it observationally and theoretically so challenging to find and form these `gargantuan' black holes and in which environments are they most likely to be found? Is it possible to disentangle their duty cycle and the likely dust obscuration to constrain their number density?
2. What is the likely impact of these ultra-massive black holes on their host galaxies and how could we potentially detect them with the current and upcoming observational facilities, such as ALMA, JWST and Athena?
3. By observing these objects at z ~ 6 what can we learn about their progenitors and can we set constraints on the black hole seed mass distribution and on their growth efficiency? To understand these issues, why it is so important to push the high-redshift frontier and are there any other future observational means that will allow us to probe black holes up to the `Dark Ages'?

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Cosmology with Fast Radio Bursts (FRBs)

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Room: H57

Essay Description

Fast radio bursts (FRBs), transient radio signals of yet-unestablished nature, may prove to be new and unique cosmological probes, thus complementing the picture of the Universe that we draw based on the measurements of the cosmic microwave background (CMB) and surveys of the nearby cosmos.

FRBs are narrow pulses of radio signals, which are significantly dispersed by the ionized medium distributed along the path between the source and the observer. For most of the detected FRBs, the observed dispersion of FRB pulses, quantified in terms of dispersion measure (DM), is much larger than the contribution of our local environment. Therefore, it is now known that the overwhelming majority of FRBs are of extragalactic origin.

By exploring the dependence of DM on the cosmological redshift, one can extract information about the composition of the underlying Universe and probe its expansion history. At low redshifts, FRBs have already proven to be valuable cosmological probes. It has been shown that dependence of DM on the cosmological redshift, z, of the FRB hosts could pin down properties of the intergalactic medium (IGM) and probe cosmological parameters. To give an example, with a sample of localized low-redshift FRBs (host redshifts of $z < 0.66$), Macquart et al. (2020) showed that the dispersion measure of these transients depends on the baryonic content of the Universe (along the line of sight) and, thus, can help identifying the missing baryons in the IGM by counting the total number of baryons along the line of sight. For higher redshift FRBs, beyond the current observational cut-off of $z\sim3$, theoretical predictions show that a population of FRBs at $z = 3$–4 could be used to constrain helium reionization occurring around redshift $z\sim3.5$, while signals from $z > 5$ would primarily trace the evolution of the hydrogen ionization state, and, thus, probe the epoch of reionization.

The goal of this project is to review the status of the field and explore FRBs as cosmological probes at low and high redshifts.

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