Basic Information

Title:

Alternative Explanations for Cosmic Acceleration in the Dark Universe

Short Abstract:

Understanding the accelerating expansion of the Universe remains one of the most significant challenges in cosmology and theoretical physics. While commonly attributed to Dark Energy, its nature is unknown. Competing explanations include the cosmological constant, new types of fields, modifications to General Relativity on large scales or apparent effects due to cosmic inhomogeneity. My proposed MSc research will explore one or more of these possibilities by developing theoretical and computational tools to analyse alternative cosmological models and test their consistency with observational data.

This research is motivated by the need to interpret data from future surveys such as the Square Kilometre Array, the Dark Energy Survey, and EUCLID. These observations require theoretical frameworks for testing current assumptions in cosmology. Depending on the direction that emerges during the course of the research, I may focus on modified gravity models that adjust Einstein's equations, explore model-independent frameworks that reconstruct expansion without relying on specific theories or study the influence of cosmic inhomogeneity on our interpretation of large scale data.

The research will combine mathematical modelling with computational methods to derive and simulate predictions from various theoretical approaches. The aim is to produce observational predictions that can be tested using cosmological datasets, including large scale structures, supernovae and lensing surveys. The work will contribute to a deeper understanding of cosmic acceleration and to the broader development of theoretical and computational approaches in cosmology.

Project Outline

The observed accelerating expansion of the Universe presents a major challenge to our understanding of gravity and cosmology. This phenomenon is typically attributed to Dark Energy, believed to make up around 70% of the universe's total energy content. However, its nature remains unknown and the mechanisms driving acceleration are still poorly understood. My proposed MSc research will contribute to the investigation of this problem by developing and applying theoretical and computational tools to explore a range of alternative explanations for cosmic acceleration and assess how they compare to the standard model of cosmology.

Several possibilities have been proposed to account for the observed acceleration. These include the cosmological constant originally introduced by Einstein, new types of fields, large scale modifications to General Relativity and systematic effects arising from cosmic inhomogeneity. When future surveys, such as the Square Kilometre Array (SKA), the Dark Energy Survey (DES), and EUCLID, provide new data, there will be a need for theoretical frameworks capable of interpreting this information and testing current assumptions underlying cosmology.

One possible research direction involves examining modifications to Einstein's theory of gravity. These theories propose that General Relativity requires modification on cosmological scales to explain the observed acceleration of the universe. This would involve investigating $f(R)$ gravity models, which introduce additional curvature terms into Einstein's equations, by deriving their exact solutions and computing observational predictions [1,2,3,4]. This work will determine whether such modifications remain consistent with cosmic microwave background data, large scale structure observations and Type Ia supernova measurements [5,6].

Another area involves developing model-independent techniques to evaluate cosmological expansion. Cosmography, for example, assumes large scale homogeneity and isotropy and offers a framework-independent way to test the standard model [7]. While this method avoids dependence on specific gravitational theories, it has been shown to suffer from a number of issues. There is work that can be done to investigate improved formulations of this approach, explore new auxiliary variables and validate these ideas through simulated datasets based on the expectations of upcoming surveys.

A further possibility is to consider whether cosmic acceleration could be an apparent effect caused by the way inhomogeneities are treated in cosmological modelling. The standard model assumes large scale homogeneity, yet the Universe contains significant structure at small and intermediate scales. The influence of inhomogeneities may lead to corrections in the average cosmic expansion that are not captured in homogeneous models. This research could examine whether these effects are significant enough to account for the observed data, potentially offering an explanation for acceleration that does not require Dark Energy or modified gravity [8,9].

Methodologically, the project will combine analytical modelling with computational implementation. This may involve deriving and solving perturbation equations for different gravitational frameworks without relying on commonly used approximations such as fixed background evolution or the quasi-static limit [10,11]. Avoiding these assumptions allows for a more general and potentially more accurate treatment of cosmological structure and dynamics. Where applicable, existing computational tools used in cosmological data analysis may be modified to incorporate the effects of alternative gravity models or inhomogeneous spacetime structure.

Observationally, the theoretical predictions produced by the models under investigation can be compared to datasets. These include measurements of large scale structure, weak gravitational lensing, baryon acoustic oscillations and supernovae [5,6]. By comparing the predictions from different frameworks to this data and analysing the results using appropriate statistical tools, the research will help assess the plausibility of various competing explanations for the acceleration of the universe.

The project is aimed to remain flexible and exploratory, reflecting the wide range of open questions and theoretical possibilities in the field. Rather than committing to a specific model or approach at the outset, the research will adapt to both the interests and strengths I develop during the course of my MSc. Whether the focus turns more toward modified gravity, model-independent testing, inhomogeneous cosmology or a combination of these, the overarching aim will be to test the foundations of current cosmological models and contribute to our understanding of the Dark Universe.

This research will provide training in theoretical physics, cosmology and applied mathematics. It will also develop technical skills in analytical problem solving and numerical modelling. These skills are valuable for future work in academic contexts and will contribute to national goals in expanding expertise in the mathematical and physical sciences. By investigating one of the most important open questions in cosmology, this project aims to support and advance South Africa's role in scientific research.

References

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Alignment to National Imperatives

NRF Broad Categories:
Mathematical Sciences

Justification:
My research develops and applies mathematical methods including differential geometry, perturbation theory and numerical modelling to investigate cosmic acceleration, test alternative gravity theories and analyse cosmological data.

National Priorities:
Transformation

Justification:
This research supports transformation by informing outreach initiatives with advanced cosmology, making science more accessible to underprivileged communities and helping to broaden participation in STEM in South Africa.

National Strategy:
Grand Challenge: Astronomy

Justification:
My research explores questions in cosmology, focusing on dark energy and gravity, supporting South Africa's investments in astronomy through instruments like the SKA, while developing theoretical frameworks to interpret the data produced.

Sustainability Development Goals:
Industry Innovation and Infrastructure

Justification:
My research develops theoretical tools that support infrastructure like the SKA, reinforcing South Africa's role in global astronomy, strengthening research capacity and driving scientific innovation.

Quality Education

Justification:
This project contributes to quality education by expanding local expertise, inspiring postgraduate training and strengthening the scientific knowledge base in South Africa.

Gender Equality

Justification:
My research promotes gender equality by showing that women can succeed in a male dominated field, inspiring more women to pursue STEM (science, technology, engineering, and mathematics) careers and helping to create a more inclusive academic environment.

Science Engagement

Category:
Science and Communication

Why is the engagement being undertaken:
My participation at the Cederberg Observatory aims to raise public interest in astronomy by guiding telescope nights and sharing accessible explanations of the night sky. The goal is to spark curiosity and improve general science awareness.

Audience:
Indeterminate/broader public

How will you engage with said audience:

We engage the broader public through regular astronomy evenings at the Cederberg Observatory. These sessions include accessible presentations followed by guided telescope viewing. Visitors are introduced to objects visible in the night sky, such as planets, star clusters and nebulae, with explanations that suit a general audience.

The aim is to make astronomy understandable and interesting without requiring prior scientific knowledge. We encourage questions and adapt the level of detail based on the group. The environment is informal, which allows people to engage at their own pace and develop a better understanding of basic astronomy and the scale of the universe. My MSc research on cosmic acceleration and dark energy allows me to share cutting edge cosmological discoveries and explain the importance of surveys like the Square Kilometre Array. I also designed the Cederberg Observatory's website to improve accessibility and outreach (https://www.cederbergobservatory.org.za/).

This approach helps build general science awareness and encourages public interest in astronomy. It also provides an opportunity for people to interact directly with science, outside of a classroom or formal setting.

How will you asses the broader impact of science engagement initiatives:

I assess the broader impact of this science engagement through a combination of informal observations and encouraged feedback. During sessions, I pay attention to the types of questions asked and how engaged visitors are throughout the experience. We also invite attendees to share their thoughts in a visitors book or online, which provides insight into what aspects they found most interesting or informative. Over time, I will also track attendance numbers and observe the diversity of the audience. These simple methods help evaluate how effectively the sessions promote science awareness and guide any future improvements.

Category:

Community engagement projects

Why is the engagement being undertaken:

I am involved in the development of the outreach initiative Zulelinye which engages children from underprivileged communities with science using astronomy as an entry point. The name means “one sky” in isiXhosa, reflecting the idea that we all share the same sky regardless of background. The project aims to create opportunities that spark curiosity, build confidence, and promote interest in science by making learning more accessible and inclusive.

Audience:

Learners (school)

How will you engage with said audience:

Zulelinye engages learners through engaging sessions held in schools or community spaces. Activities include sky observation, storytelling and hands on experiments that introduce basic science concepts in a fun and accessible way. The content is adapted to suit different age groups and delivered with the help of teachers or local facilitators when possible.

Sessions focus on participation and curiosity rather than didactic teaching. Learners are encouraged to ask questions, explore ideas and connect science to their everyday experiences. The goal is to create a relaxed environment where children feel confident to engage and learn. My research into cosmic acceleration provides material for explanations about space expansion and dark energy, helping learners connect what they observe to cosmological questions.

Through this practical approach, learners connect what they see in the sky to broader scientific ideas, while developing skills in observation, reasoning and communication.

How will you asses the broader impact of science engagement initiatives:

The impact of Zulelinye will be assessed through feedback from learners, teachers and facilitators, as well as observations of learner engagement during activities. We will track participation numbers, note changes in interest or confidence over time and gather reflections from educators to understand how the project supports learning. As the initiative grows, we aim to develop more structured assessment tools, such as short surveys or creative outputs from learners, to evaluate how effectively the programme promotes curiosity, science engagement and educational inclusion.