The Data Behind Dark Matter: Exploring Galactic Rotation

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Summary

By analyzing the rotational velocities of bodies in galaxies, physicists and astronomers have found that there seems to be something missing in our understanding of these galaxies. One theory is that there is some invisible matter present that does not interact with light — that is, these galaxies contain dark matter (Rubin et al., 1978).

Participants in this workshop will have the opportunity to explore dark matter through scientific literature-based (Fraternali, F. et al., 2011; Jimenez et al., 2003; Karukes, E. V. et al., 2015; Naray et al., 2008; Richards et al., 2015) galactic rotation curves both by using interactive programs and by editing Python code. This will give participants an understanding of how physicists arrived at the idea of dark matter, showing them the difference between curve fits with and without dark matter components. Understanding dark matter's epistemological origins will help participants formulate their own opinions on the dark matter debate.

Materials

This project consists of several modules in the form of Jupyter notebooks (Kluyver et al., 2016):

File Name	Description
01_DM_Rotation_Curve_Intro.ipynb	Animations and rotation curve plots demonstrating three types of rotational motion.
02_Widget_NGC5533_DMonly.ipynb	Interactive widget to introduce dark matter.
03_Measured_Data_Plotting.ipynb	Rotation curve plotting of measured velocities to visualize star and gas motions in a galaxy.

File Name	Description
04_Plotting_Rotation_Curves.ipynb	Plotting the rotation curves of galaxy components.
05_Widget_NGC5533_All_Components.ipynb	Interactive widget to visualize the components of the galaxy NGC 5533.
06_Plotting_SPARC_Data.ipynb	Plotting the components of galactic rotation curves using the SPARC database of 175 galaxies.
07_Bonus_Bulge_Rotation_Curve.ipynb	Constructing a rotation curve for the bulge component using empirically-derived parameters.
08_Interactive_Fitting.ipynb	Interactive curve fitting.
09_Widget_SPARC_Galaxies.ipynb	Interactive widget to visualize the components of multiple galaxies using the SPARC database.
10_Bonus_Black_Holes_as_DM.ipynb	Considering tiny black holes as dark matter candidates.

Statement of Need

The primary goal of our project is to present rotation curve development and research in a versatile and approachable format for anyone to explore, learn from, and build upon. Rotation curves are a key empirical artifact through which dark matter can be observed and analyzed (Rubin et al., 1978); however, a thorough, start-to-finish description of the rotation curve building process is typically not given in scientific publications. Furthermore, software tools used in rotation curve literature are generally difficult for inexperienced users; for example, the GIPSY software package is very thorough but does not provide any introduction as it is intended for experienced users with a firm grasp on rotation curve components (Kapteyn Astronomical Institute, 1992). Therefore, a rigorous yet accessible learning module is needed to provide an entry point for any individual interested in investigating the effect of dark matter in spiral galaxies. Our workshop is designed to present a convenient platform for developing basic rotation curves focused on introducing newcomers to the concepts necessary for understanding galactic rotation. This is achieved by leading users through hands-on computational activities, including building and plotting their own rotation curves.

Learning Objectives

The learning objectives for these modules are:

1. Provide a working space where people can connect with current literature and identify as scientists.
2. Educate curious students or other individuals on the basic concepts of rotation curves, as related to the current problems and mysteries regarding dark matter in the universe.
3. Provide users with accessible activities relating to the basic principles of rotation curve composition. This includes:
   a. facilitating the introduction of rotation curve concepts via open-source code.
   b. interactive programs to provide users with practical and tangible approach of what producing rotation curves involves.
4. Understand data and models by interacting directly with equations and figures.

Most of the content provided in these modules has been presented and taught in previous workshops/research symposiums (University of Colorado Denver: Data Science Symposium 2021 (Villano et al., 2021), Research and Creative Activities Symposium 2020 (Harris et al., 2020), 2021 (Harris et al., 2021), and 2022 (Harris et al., 2022)) with feedback collected from participants. We have chosen the activities for this module that proved most successful in terms of education and sparking interest.

Delivery

The modules are designed to be presented to participants in numeric order as part of a workshop, skipping those marked as "Bonus" as needed to fit the alloted time. Participants are encouraged to work together to complete the modules and compare their results to one another. While working through a module, the instructor(s) should be available to answer questions and check in on participants' progress, but they should leave the bulk of the work to the participants themselves. If any bonus modules are being skipped, the instructor(s) may wish to suggest them to participants who find they are completing the content ahead of schedule.

All materials are designed to work on myBinder.org (Jupyter et al., 2018), a website for hosting and interacting with jupyter notebooks. This is done to allow people to participate in the workshop without needing to install any software beforehand and is treated as the default delivery method. Participants who are experienced with python and already have a jupyter environmental installed may choose instead to run the modules locally.

Story

This project emerged from years of literary analysis and studying the reproducibility of rotation curve research. This journey impressed upon us a lack of clarity and accessibility for newcomers in the world of rotation curves, not only in publications, but also in using software and acquiring pre-existing data for rotation curve composition. The problems we encountered stemmed from the resources we found being very dense with technical language, focusing heavily on one or two components or even parameters, or assuming the reader has a certain level of familiarity with the subject prior to finding the resource in question. These traits are favorable for scientific journal content, but the lack of other types of content made it difficult to find an entry point to the field. Our solution at the time was to dig into Noordermeer's paper on flattened Sérsic bulges (Edo Noordermeer, 2008), a paper that took us roughly a year to reproduce as we followed chains of references, corresponded with authors, and tried out rotation curve construction software in order to understand each rotation curve component. What we hope to accomplish is to provide

others with necessary vocabulary and background knowledge before prompting them to explore this kind of literature. Based on this experience and on feedback from our previous workshops and presentations at research symposiums, we have developed our own software with a focus on improving accessibility and users' understanding of the material by being clear, concise, and easily reproducible.

Acknowledgements

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