Metallicity in the Early Universe as a Probe for Galaxy Physics: Laying the Groundwork for JWST

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Background

Current state-of-the-art galaxy simulations are at an impasse. While the Λ-cold dark matter (ΛCDM) model is hugely successful at predicting the evolution from the early Universe to the large scale galactic structures that we see today, there are key tensions that preventing us from fully accepting it. One such tension is the core-cusp problem (illustrated in Figure 1; Moore 1994). In dark matter simulations of ΛCDM, a galaxy's density profile is "cuspy" – it increases at small distances from the center. On the other hand, observations find that the density profiles are "cored", the density is roughly constant at small radii. Many solutions proposed to alleviate the core-cusp problem call for completely abandoning the well-established ΛCDM model. One solution, however, allows us to keep ΛCDM: increased volatility in the feedback from stars (Mashchenko et al., 2006). The increased volatility is quite effective at rapidly modifying the central potential, allowing the dark matter to move outward from the center of the galaxy and "coring" the density profile. However, the effects that this increased volatility has on the rest of the galaxy are not yet fully understood. In this project, we plan to explore the effects that increased volatility on the observable gaseous component of galaxies. We will be able to further understand the nature of dark matter in our Universe by first understanding the effect of stellar feedback on the gas of galaxies.

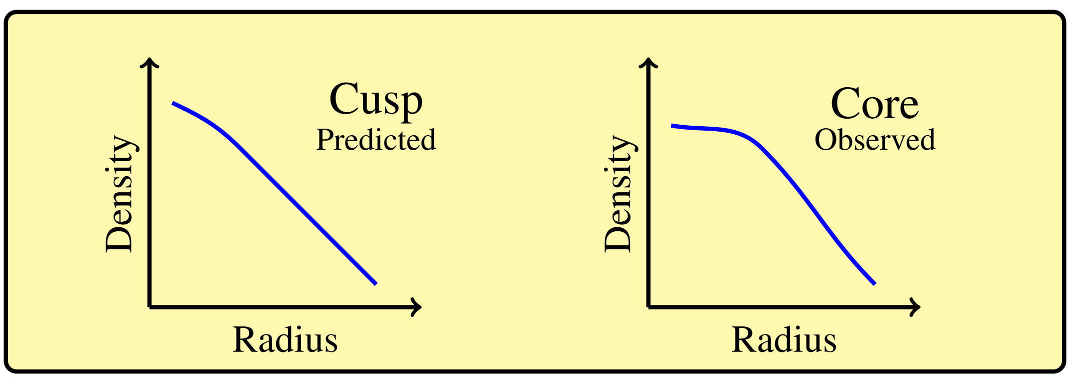

Figure 1: Illustration of a cuspy dark matter profile (left) and a cored dark matter profile (right). Cores are what we observe, while the cusp profile is expectations from dark matter galaxy simulations.

One promising method to understand the impact of increased volatility comes from how the metal content, or metallicity, is spatially distributed. Heavy metals are synthesized in the cores of massive stars and are ejected back into the interstellar medium (ISM) via supernovae and stellar winds. Consequently, stellar feedback mechanisms help determine the rates at which the metals mix with the existing gas, redistribute through the galaxy, and are ejected from the galaxy entirely. The net effect of this complex interplay is that the metal content in the gas of galaxies is highly sensitive to the ongoing (and previous) feedback processes. The increased volatility model suggests that stars are formed in rapid "bursts". These bursts lead to a large, contemporaneous population of massive

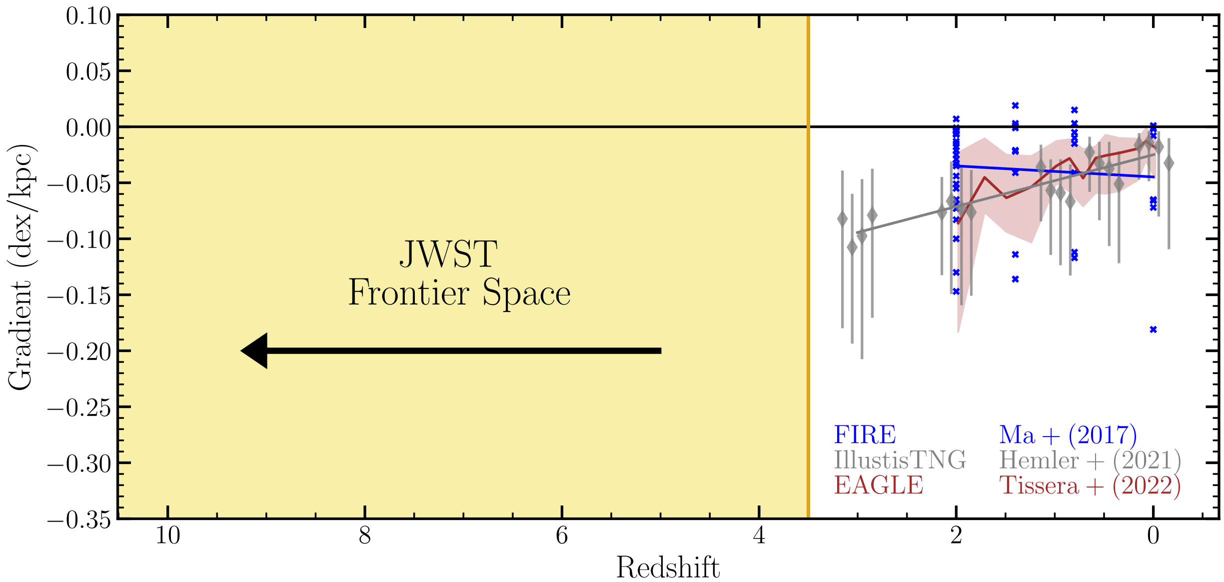

Figure 2: Evolution of metallicity gradients for star forming galaxies in simulations. Further left on this plot is further back in the history of the Universe. Note the hint of disagreement between the bursty (FIRE) and non-bursty (IllustrisTNG and EAGLE) models at low redshift. Low redshift data courtesy of Ma et al. (2017); Hemler et al. (2021); Tissera et al. (2022).

stars that all enter their end stages around the same time. This model leads to three key predictions: (i) the supernovae associated with stellar deaths release an enormous release of energy, (ii) the massive energy release – when coupled to the galactic gas – leads to a massive outflow, and (iii) the rapid expulsion of gas leads to a rapidly changed potential well. The net effect of these bursts is to rapidly redistribute gas (and the metals within) throughout the entire galaxy. The other model, non-bursty or smooth, suggests that stars form and die over a much longer time. Since the deaths of massive stars are more staggered, a key prediction of these models is that feedback will have an overall less significant impact at any given time. As such, non-bursty feedback models predict that metals can more effectively build up in locations with a large number of stars.

Literature To Date

The spatial distributions of metals are most commonly measured radially. The centers of galaxies predominately have more metals than the outskirts in both simulations (e.g., Pilkington et al., 2012; Gibson et al., 2013; Yates et al., 2021) and observations (e.g., Searle, 1971; Magrini et al., 2007; Grasha et al., 2022). Typically, the metallicity profile of a galaxy is fit with a linear regression. A metallicity gradient is determined by the sign of the slope of the regression. Galaxies, then, are said to typically have negative metallicity gradients.

The metallicity gradients have been shown to be particularly sensitive to the feedback mechanisms throughout the life of the Universe, however (Garcia et al., 2023; Hemler et al., 2021; Gibson et al., 2013). This fact is demonstrated in Figure 2 comparing the strength of metallicity gradients (measured in units of dex[1]/kiloparsec) as a function of redshift[2]. The bursty feedback model FIRE (blue) shows a lack of evolution through time. This is a direct consequence of the increase volatility of stellar feedback: the massive outflows take the metallicity and rapidly redistribute it through the galaxy, flattening the gradient. On the other hand, the non-bursty feedback models IllustrisTNG (gray) and EAGLE (red) show metallicity gradients that increases in strength going further back in the lifetime of the Universe. This is because there is no equivalent mechanism to wash out gradients. The difference between these models is rather subtle at redshift $\lesssim 2$, yet hints of a bigger discrepancy further back in time are seen. Further examination at high redshift within these theoretical models is required to understand the full scope of the disagreement

Our Approach

We will use data from Feedback In Realisitc Environments (FIRE; Hopkins et al. 2014), IllustrisTNG (Pillepich et al., 2018), and Evolution and Assembly of GaLaxies and their Environment (EAGLE; Schaye et al. 2015) galaxy simulations. The FIRE model is currently the flagship bursty stellar feedback model, while IllustrisTNG and EAGLE are the flagship non-bursty feedback models. Each of these simulations' data products are publicly available.

We will combine these datasets for the first time in the literature. In order to ensure fair comparisons, we will dedicate time to developing a common framework on which each simulation's metallicity gradients will be evaluated. This will involve combining aspects of all previous works in each simulation at low redshift (see Ma et al., 2017; Hemler et al., 2021; Tissera et al., 2022). The unique approach we aim to take is to expand the sample of galaxies further back in time, laying the groundwork for follow-up observations to (hopefully) provide a clean resolution to the feedback volatility question. This, in turn, will help inform our understanding of the nature of dark matter in our Universe.

NASA Application of This Study

NASA is host to the best instrument capable of making these critical measurements in the early Universe: the James Webb Space Telescope (JWST). Metallicity is determined in observations using emission lines that all appear in the optical part of the spectrum (Kewley et al., 2019). Past a redshift of ~ 3, however, these nebular emission lines are shifted into the near infrared (IR), meaning they are entirely inaccessible to optical instruments (e.g., Hubble Space Telescope). Therefore, metallicity measurements in the early universe will need to come from a near IR spectrograph, i.e., NIRSpec on JWST. The theoretical framework provided by this project is a potentially eye-opening discovery in the field of galaxy evolution which should opens questions that NASA can answer uniquely with JWST.

Timeline

We anticipate this project will take approximately ten months for completion. In the first month, we will collect all publicly available data onto our local high performance computing cluster and construct preliminary analysis pipelines. In the next two/three months, we will develop an even-handed methodology for comparing the different simulations. The next two/three months will be spent comparing the simulations' gradients and understanding our results. The remaining time will be used to write a publication describing our findings.

[1] dex: Decimal EXponent. The traditional units of metallicity, which is a logarithm of the ratio of masses: $\log \mathrm{O/H}$

[2] Redshift: Proxy for the age of the Universe. An observationally motivated parameter corresponding to how much an object's spectrum has been shifted towards "redder" wavelengths due to the expansion of the Universe. A higher redshift implies further back in the history of the Universe.

Academic Statement

Alex Garcia, University of Virginia

Graduate Career:
My graduate career has been somewhat unconventional to this point, having attended both the Universities of Florida and Virginia. I began my Master's program at the University of Florida working with Paul Torrey in August 2021. During my time at Florida, I established myself in the field in four different ways: (i) research through a first-author publication, (ii) teaching multiple courses including an intensive lab course, (iii) in the classroom by earning a 3.97 GPA in graduate-level coursework, and (iv) outside the traditional academic scope through my role at the local planetarium. In Fall of 2023, Paul and I transitioned into positions at the University of Virginia. My time at Virginia has been characterized with: (i) another first-author publication and another very late stage draft, (ii) outreach with a graduate-student lead group, (iii) co-hosting the department's journal club, and (iv) teaching multiple courses.

In summary, my relatively short career has, to this point, resulted in two completed first-author publications (https://academic.oup.com/mnras/article/519/3/4716/6960583 and https://arxiv.org/abs/2401.12310), another project in late-stages development, a large amount of teaching experience, and a lot of outreach opportunities. Thus, my time at both Florida and Virginia has been well-distributed in terms of learning, researching, and performing outreach in the community. I feel well-positioned to continue my research success with this proposed project, in addition to continuing my active involvement within the community through outreach.

Post-graduation goals:
My primary professional goal is to become a full-time researcher studying galaxy formation through the lens of cosmological simulations. I am aware that at every career-stage interface lies a significant potential barrier to overcome. Therefore, I plan on making conscious efforts to craft all aspects of the body of my Ph.D. work into a highly competitive post-doctoral application. I plan to take on 1-2 post-doctoral positions after graduating. I will continue my studies of how galaxies evolve throughout cosmic time and hopefully devise new methods for breaking decades-old tensions in the field. After my time as a post-doc, I hope to become a research professor at an R1 university. I enjoy interacting with more junior students by supporting and encouraging their scientific development. In addition, through my many experiences teaching, I have gained a sincere enjoyment for being in the front of the classroom. The best way to combine these two passions is through becoming a professor.

Relevance to NASA Mission Directorate

Alex Garcia, University of Virginia

This project is relevant to the Astrophysics Division of the NASA Science Mission Directorate (SMD). A key goal of the astrophysics division of the SMD is to understand “how does the universe work?”. Included in the scope of this question is the nature of dark matter. We will help uncover the nature of dark matter by understanding of the role that volatile stellar feedback has on the gas within galaxies. As mentioned in the research statement, Lambda CDM, our best theory for the evolution of the Universe, is potentially in peril. If volatile stellar feedback creates metallicity gradients that are not observed, Lambda CDM would have a serious unresolved tension. Requiring modifications to Lambda CDM would be a paradigm shift in our understanding of our Universe. Developing a theoretical understanding of the effect of volatile feedback is therefore critical to interpreting upcoming JWST observations of the early Universe.

A second key goal of the astrophysics division is to “explore the origin and evolution of the galaxies, stars and planets that make up our universe.” Understanding the impact of stellar feedback on galaxies is not only critical for our understanding of dark matter, but galaxy evolution as a whole. This project will help enable a more complete understanding of how galaxies assemble over an very broad time range (over 10 billion years).

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