

From Cosmic Dawn to Modern Universes: Multi-Messenger Observations in Galaxy Formation Studies

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Abstract. This paper looks at thoughts on galactic creation and growth from cosmic dawn up till today and also how these thoughts changed multi-messenger astronomy. Multi - messenger astronomy uses observatories on Earth and in space observing every wave length, Gravitational waves, neutrinos, and cosmic rays give a better picture of what fields are driving the transition between galaxies on an astrophysical timeline. In this project it explains all the fields involved in how galaxies form, starting with the Cosmic DAWN phase -Dawn meaning the birth - where the first stars, first galaxies, and first supermassive black holes are formed. This paper speaks about what has been learned from observing high-redshifts through the help of the Hubble Space Telescope (HST) and James Webb Space Telescope (JWST). population III stars, further early star-forming burst galaxies, and issues caused by of the early universe shall be considered. It is hopefully that this paper excites someone about those knowledge gaps, prompts some more research on them, and gives an enthusiastic introduction to the power of multi - messenger astronomy to answer some of big problems.

Keywords: Galaxy formation, Cosmic Dawn, Multi-messenger astronomy, High-redshift surveys

1. Introduction

It includes all time and space scales, it starts from the very first moment when galaxies formed, that's called the Cosmic Dawn, and it goes all the way to now, and galaxies people can observe with their complex histories and diversity [1]. In order to understand this process, gas dynamics, star formation, feedback, black hole growth, and their interconnections, must be investigated over cosmic time. Recent advances in astrophysical observations and theoretical developments have now taken to a point where the primary processes by which galaxies form, evolve and interact with their environments are considerably better understood [2].

Recent advances in multi-messenger astronomy will be beneficial for these advances as they bridge electromagnetic observations with gravitational waves, neutrinos, and cosmic rays [3]. Combining these messengers increases sensibility to astrophysical phenomena as it reveals new aspects of galaxies via new observations of these phenomena. Some of these new events include gravitational wave detections with neutron star mergers [4], active galactic nuclei (AGN) feedback [5], and reionization in the early universe [6]. The combination between different observational

methods help overcome limitations inherent in single-messenger studies, offering new insights into the physical processes governing galaxy formation.

High-redshift observations, particularly using the HST (Hubble space telescope) and James Webb Space Telescope (JWST), have provided a new way of understanding early galaxies [7]. These instruments uncover the characteristics of the first stars (Population III) and starburst galaxies [8], and provide a great insight into the initial conditions of cosmic structure formation. But challenges in observing faint and distant objects and their spectra are still existing due cosmological redshift and interstellar medium [9]; techniques to address these challenges are continually being refined, as discussed in [10].

In this paper, this paper reviews key processes in galaxy formation, from the Cosmic Dawn to present, using a multi-messenger observations approach. There will be several reviewing according to the early formational processes of both stars and black holes, the implications of recent high-redshift surveys, and the importance of gravitational wave and neutrino astrophysics. By adopting and synthesizing multiple observational techniques, and integrating insights from large-scale cosmological simulations such as IllustrisTNG [11], the aim is to provide a cohesive understanding of the evolution of galaxies and identify avenues for future research in this rapidly evolving field as outlined in the prospectus by [12].

2. The Cosmic Dawn and early galaxy formation

The Cosmic Dawn is a momentous time in the early history of the universe representing the birth of the first light in the universe in the form of primordial stars, galaxies, and black holes. The Cosmic Dawn started around 100 to 200 million years after the Big Bang, and it represents the end of the cosmic “dark ages” and the initiation of the reionization phase. Understanding Cosmic Dawn is essential for understanding how the hot, smooth, primordial universe evolved into the constantly evolving, diverse universe today. For the Cosmic Dawn, some of the most important physical processes were the gravitational collapse of dark matter halos, the ignition of the first nuclear fusion in stars, and the emergence and dispersal of heavy elements that allowed later stellar systems and galaxies to form.

2.1. Formation of the first star and galaxies

The first stars, or Population III stars, are thought to have been hugely massive, transient, and without metals. Their formation and death sculpted the nascent intergalactic medium through radiative feedback, supernova events, and metal enrichment. They also seeded the first supermassive black holes, and their growth and activity affected galaxy evolution through feedback. At the same time, the first protogalaxy began to form during the densest areas of the cosmic web, with formation from hierarchical merging and fast gas accretion. They were likely compact, turbulent, and had starburst activity, which made a substantial contribution to the ultraviolet photon budget that drove cosmic reionization.

2.2. High-redshift galaxy surveys

Observational knowledge of this period has been greatly enhanced by high redshift galaxy surveys with space telescopes, particularly with HST and, more recently, the JWST. space telescopes have detected and characterized galaxies at even higher redshifts of $z \approx 10$, thus allowing access to the hugely informative early stages of the assembly of galaxies. Furthermore, JWST, with its

extraordinary infrared sensitivity, is beginning to expose populations of faint, high redshift galaxies whose properties disaffirm current models for the timing and nature of early star formation and galaxy growth. Other, more indirect probes such as the cosmic microwave background (CMB), or quasar absorption spectra, complementarily specify the timing and completeness of reionization, as well as the properties of the early sources of light.

2.3. Challenges in studying the earliest stages of galaxy formation

There are still great challenges in examining the earliest stages of galaxy formation, notwithstanding these advancements. Observing the first stars and protogalaxy will likely be limited by cosmological redshift and will also require exceptional sensitivity in the infrared as well as the submillimeter portions of the spectrum in order to do so directly. Furthermore, theoretical models of the first forming galaxies and stars can be based on simple physical theories, they must still model much more complex multi-scale physics e.g. gas cooling, star formation efficiency, the multiple forms of feedback, along with the interplay between the matter and the radiation. Clearly, the intrinsically faint and rare features of Population III stars, as well as the systems hosting them, remain great observational hurdles. Multi-messenger methods (for example, by combining the electromagnetic information can be collected with gravitational wave information from direct mergers of compact objects in the early Universe, or neutrino emission from the antecedents of a class of supernovae, both of which will contain a wealth of additional information) may provide new systematic pathways to gain insight into this first epoch, and ultimately provide a dramatic way to complete the view of the formation of cosmic structure.

3. Multi-messenger observation in galaxy formation studies

People who study how galaxies form and make changes can learn from something called multi-messenger astronomy now. Taking old electromagnetism observations, and these cool new toys like Gravitational Waves and Neutrinos and Cosmic Rays, people have a chance to test out different physics and probe different places at different times. Knowledge created using a multi-messenger angle allows for more fullness of baryon cycling occurring in and around galaxies, feedback processes occurring in and around galaxies, transport of energy between galactic systems, and many caveats that would probably get hidden from observation by each messenger and observer individually. Concluding that creating neutral coupling for both messengers to have a more coherent representation of the galactic setting and galactic evolution will also have a huge role.

3.1. Electromagnetic tracers of baryonic components

Electromagnetic observation is still the most beginning step in the research of a galaxy - In the optical and infrared, (these tell about those stars like what they are, when did they form, histories of their star formation and how metal distribution looks, observations of stellar are needed to understand its secular changes in shape.) X-rays are good for seeing stuff in space with lots of energy, so it is easy to see gas going into really big black holes and see how stuff around galaxies is growing. Observations via Radio measures cold gas, this is done with the use of 21 cm line which gives some indication of what maelstroms of fuels are out there – and how might draw on those in the future as fuel for star formation, and what the motions and dynamics of gas and dust are within the interstellar medium.

3.2. Gravitational waves as probes of dynamic evolution

With the detection of gravitational waves, a light shines onto the active production of galaxies, and many of these come to light; there being many places where the collision between compact object (like binary black holes, neutron stars, etc.). Merges into compact objects, which give information about the population and merger history of these compact objects, which are closely related to the history of star formation and dynamics interactions with host galaxies. In addition, how often and what masses those mergers occurred at could be found out, which would then give a way to indirectly bound when and how massive black holes formed and grew in the past and give a small hint if there is a link to the mass of the host galaxy.

3.3. High-energy messengers: neutrinos and cosmic rays

Like neutrinos again, it shines as a tracer of an event, but these are so much more evasive from a rest of other wavelength band's tracer: like neutrinos again: Neutrinos, being very weakly interacting particles, could still escape even from something like the stellar core or an accretion disk, so they're a very direct window for looking at how particles get accelerated and hadronic interact. Cosmic rays helps it to ionized and control the energy budget to create stars which creates flow. But but like a gamma ray burst or supernova right you could detect one So once more, it's like you know that is something that you're learning, right, as an input into, oh, the ecosystem in the galaxy.

3.4. Synergistic insights from multi-messenger astronomy

To have available for an astrophysical interpretation at least a few observable messengers is good. The example of maybe something could work with as close to if at all were able to find that electromagnetic counterpart to a gravity wave event and map it, so the study could then know what is passing through its environment for a moment. Something like that would be EM and Neutrinos, so the study has two kinds of observations that will allow to put constraints on models for particle acceleration and particle movement as well. These combinations give fresh ways to break up the degeneracies in transient even interpretations and the transients can themselves create all new classes of phenomenon, which can enhance understanding of the physics of galaxy formation.

4. Tracing galaxy evolution across cosmic time

To get a handle on any galaxy's bygone, the study would require as much as is feasible in cosmic time as large a stretch of time as possible that goes back as long ago as to the beginning of galaxies and keeps going right through current era. Big, multi-color searches and long-time searches let people follow structure development, star making history, and feedback through tons and tons of years and show what different galaxy changes happened at different times. Like seeing galaxy fights, getting things sucked in from the outside, and stuff bouncing off neighbors. Combined with these, plus the modern numerical models, they should give a better idea of which galaxy followed which evolutionary path through the cosmic web as it evolved.

4.1. Star formation and mass assembly through cosmic epochs

Galaxies go through different phases for birth with stars and adding matter. Cosmic noon occurs when cosmic star formation hits its zenith. There's a lot of mergers, starburst of galaxies, where a galaxy will explode into a bunch of stars. Late Universe has less star formation, quenching is more

important, and passive and morphological settling. And then the big surveys, SDSS, Euclid, Roman space telescope, it counts to know the stats on what's changing with distance, like redshift.

4.2. Feedback and the baryon–dark matter connection

The relationship between baryon matter and dark matter is quite relevant to the evolutionary process of the galaxy, and the feedback of the explosion of stars and the wind of stars and active galactic core nuclei. Feedback process controls star formation and produces out metal during galactic evolution but changes the distribution of dark matter via gravitation, energy output process, and turbulence. Radio and optical surveys that continue e.g. SKA etc., will be very important in helping define the gas flows and place extremely strong constraints on this interplay which is already very complex by means of its kinematics.

5. Theoretical frameworks and simulation

Theory models plus computer models give very nice tools to figure out what is going on with all these various processes happening all over the universe of all different sizes, and tell how galaxies get up and grow. physical recipes for star formation, feedback, black hole growth, DM physics added to the sim such that the sim reproduces populations of galaxies and their evolution. and to be able to give a little more information on how good the predictions for a multiple of messengers can be and to connect a sim's physics to something can visibly see.

5.1. Cosmological simulations and synthetic galaxy populations

And today's day cosmological simulations just like ILLUSTRIS, EAGLE, TNG50 want it to be told how galaxies did create and form so far and wide as the surroundings can go. These sims generate a huge variety of galaxy properties (morphology, metallicity, star formation history, etc.), so statistically compare can be taken between them to observations. Researchers might take advantage of the models to carry out some study of mergers and accretion along with the effects of the environment all have to offer in regards to the galaxy's evolution, throughout the course of cosmic times, and possibly to see if they work together.

5.2. Connecting theories to multi-messenger observations

Like theoretical astrophysics, just to make sure simulations agree with multi-channel observations more like emitting process than just how they would be seen as gravitational waves, how many would go through and what the cosmic ray particles do within this specific galaxy. Same problem, but crossing over into other differences between simulated and observed populations, just as there were efforts to overcome the black holes' scaling relation problem or make sense of all that matter out there in those dark matter distributions.

6. Challenges and opportunities

Multi-messenger astronomy is a creative avenue for knowing the cosmos - though it does also introduce some particular technical as well as cooperative concerns. A big statistics of mixes from almost all kinds of waves like radio waves, gravity waves, neutrinos, and cosmic rays will need a very special type of work with tons and tons of science for figuring out how to mix it up and when to mix up and also how to check if it is mixed up. As for how much data, the limit on sensitivity and

the need for quick follow-up observations, these will keep causing trouble for them. Perhaps, these problems will bring the creativity and innovation when it comes to using information and building instruments. new artificial intelligence findings will be making them more efficient. The increasing importance of international relations and it might lead to new forms of integration which offer many opportunities to study cosmic neighborhood.

6.1. Technical challenges in multi-messenger observation

And another thing in Multi-messenger astronomy is like all the different data sets got from all the different messengers, wavelength is also included. with hard because the data format is different, the data time, and the space. And it is also limited by how sensitive they are, and how well they can resolve angles compared to existing observatories and so on, in much the same way that if it was neutron star mergers or supernova you'd need them to be able to localize it in the exact same way as you do for those types of transients. They need to happen fast, and it will be a challenge for when it comes to telescopes and all the data lining up right at the same time.

6.2. Advances in data science and artificial intelligence

Astronomy multi - messenger data got more and more complicated and great in size, so the advance computational ways are accepted faster. The growing use of the algorithm from the field of machine learning that was used to separate a signal and identify an event connected to many types of observation. they can make it possible to do more and more with a large bunch of bits and pieces of information, make it easier to understand why, and make a better selection of things I'm looking through that pop up less frequently. Meanwhile international involvement and data sharing platforms would be more open and reproducing or eliminate the logistical and operative difficulty of a serious astrophysics model map for good.

7. Conclusion

Multi-messenger astronomy has improved knowledge of galaxies developing and advancing from the cosmic dawn till now. The coupling of the electromagnetic observation and the gravitational waves, neutrinos and cosmic rays gave a comprehensive knowledge of baryon processes, astrophysical feedback processes, dynamical processes over cosmic times. This synthesis approach to multi-messenger astronomy reveals physical processes that are out of reach with single messenger astronomy and gives a complete picture of the building of the cosmos surveys with telescopes as big as HST, JWST which go high redshifts have an updated picture of early galaxies and Population III stars in front of them. It is useful to study about the universe when it was young so used to look at how it started, enriching metals, and getting rid of those stars in space. Gravitational Wave detections of Merging Compact Objects and High Energy Particles Give rise to Another Way to Study Black Hole Formation and AGN Feedback as well as Non-Thermal Processes in Galaxies.

Even though there has been some developments, data integration issues and observatories still being able to tell the sensitivity of the world apart as well as observatories interacting in real-time are quite big. Like anything else, machine learning, the world getting smaller thanks to social media, and future telescopes will only give me more.

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