Narrative Review Article

The Significance of Metallicity in Determining Stellar Mass

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ABSTRACT

Since Joseph von Fraunhofer's 1814 discovery of solar absorption lines, spectroscopy has become central to understanding stellar composition and the process of star formation. Building on the foundational contributions of Kirchhoff, Bunsen, and Payne-Gaposchkin, modern astrophysics has examined metallicity (the abundance of elements heavier than hydrogen and helium) as a key factor in star formation processes and the Initial Mass Function (IMF). Observational surveys and simulations suggest that metallicity influences stellar fragmentation, cooling, and feedback, with lower metallicities often favoring more massive stars. The mass-metallicity relation (MZR) and its evolution further underscore how galaxy growth, star formation rates, and feedback mechanisms influence metallicity trends over time. However, the role of metallicity remains complex and contested, with turbulence, accretion history, and environmental factors playing equally significant roles. The case of Population III stars (formed in metal-free environments) demonstrates that stellar mass can arise independently of metallicity, emphasizing the limits of a universal link between metallicity and IMF. This review synthesizes key observational evidence, theoretical models, and limitations, concluding that metallicity is a central but non-exclusive factor in determining stellar mass. Future progress will rely on integrating high-resolution simulations, advanced stellar population models, and next-generation observations, particularly from JWST, to clarify the exact relationship between metallicity and other environmental drivers of star formation.

Keywords: metallicity; spectroscopy; initial mass function; mass-metallicity relationship; enrichment; fragmentation; population III, stellar mass

INTRODUCTION

In 1814, Joseph von Fraunhofer discovered absorption lines that were inherent properties of sunlight, which came to be known as Fraunhofer lines. Though the initial purpose of this discovery was to find an objective standard for developing and testing optical glass, there were still other underlying uses to be found (1). Since the pioneering discovery of Fraunhofer lines, key developments were made by Gustav Kirchhoff, Robert Bunsen, and Cecilia Payne-Gaposchkin, all concerning the idea of the composition of the Sun.

After Fraunhofer's initial discovery of absorption lines, Gustav Kirchhoff was developing his own contributions to spectroscopy. Robert Bunsen, most well-known for the invention of the Bunsen burner used in chemistry laboratories, also made notable contributions to spectroscopy. Together, they are most well-known for the discovery of the chemical element

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caesium, also known as cesium, in 1860, along with rubidium in 1861. In collaboration with Robert Bunsen, Gustav Kirchhoff founded the science of spectroscopy, studying the spectral qualities of various chemical elements in their gaseous form. Carrying on the work of Fraunhofer, in 1859, Kirchhoff and Bunsen notably observed that Fraunhofer lines are formed when chemical elements absorb light of a certain wavelength. Furthermore, they found that different chemical elements produced different colors of flame when burned. This notable discovery firmly posited three main points. First, the existence of many chemical elements isolated on Earth was present in the Sun. Second, the majority of the Sun is comprised of a hot, incandescent liquid. Lastly, the solar atmosphere has a hot and gaseous nature. While there were subsequent improvements to their discoveries, Kirchhoff and Bunsen remain fundamental to everything known about the Sun and stars (2).

Building upon those results a century later, Cecilia Payne-Gaposchkin made a notable discovery after Fraunhofer, Kirchhoff, and Bunsen. When Payne arrived at Harvard University, she became part of a comprehensive study about stellar spectra that was already long underway. Her knowledge of the then-new science of quantum physics allowed her to understand that the unique patterns in the spectrum of any atom were determined by the electron configuration of the atom itself, and how ions are when one or more electrons are stripped away from the atom at high temperature. This information was only discovered in 1913 by Niels Bohr, quite some time after the previous contributions of Fraunhofer, Kirchhoff, and Bunsen, giving Payne an edge in terms of the conceptual understanding regarding spectroscopy. She began a long-term project and produced a thesis, in which she showed that the variation of stellar spectra is primarily due to variation in ionization states of atoms, or different surface temperatures. Therefore, the variation of stellar spectra was not dependent on the different amounts of elements. She discovered that the compositions among different kinds of stars were nearly the same, with similar relative amounts of eighteen elements. With this discovery came another, which was that all stars were comprised mainly of hydrogen and helium, while heavier elements account for less than two percent of the mass of a star (3).

The term metallicity in astronomy refers to the abundance of chemical elements that are heavier than hydrogen or helium. Metallicity can be demonstrated by emission and absorption lines using spectroscopy, a field of science that studies how light interacts with matter. That is, analysis of the spectrum of electromagnetic radiation can determine the composition, structure, and general properties of a substance. In addition to spectroscopy, measuring the brightness of an object at different wavelengths and comparing the observed colors to theoretical models can be used to estimate metallicity, utilizing photometry, the science of measuring light within the visible spectrum.

Many past studies have used metallicity as a key factor in measuring aspects of star formation, which therefore roots metallicity's importance in star formation. However, the main point of contention is the role that metallicity plays in the final mass of a star. The extent to which metallicity plays a role in star mass has been heavily disputed between astrophysicists and researchers alike. While there is an evident correlational relationship between metallicity and aspects of star formation, like the Initial Mass Function (IMF), there is a lack of profundity regarding the IMF's relationship with a star's final mass, or even the direct relationship between the IMF and star mass. The objective of this manuscript is to determine the extent to which metallicity plays a role in determining stellar mass. An effective method for achieving this objective is by conducting a literature review of numerous studies and papers regarding stellar formation, spanning from the first studies, so that a relationship between metallicity and stellar mass can be established, as well as an understanding of how the ideas of metallicity and stellar formation evolved.

FOUNDATIONS

In a similar fashion to the fundamental contributions of Joseph von Fraunhofer, Gustav Kirchhoff, Robert Bunsen, and Cecilia Payne-Gaposchkin, there have been several foundational studies and papers published during the mid-twentieth to the early twenty-first centuries (4-10). Building upon previous results, they established key ideas that have been developed and used for current research today, and they should be discussed before anything else.

One of these key studies was the study of the empirical relation between gas density and star formation, first formulated by (4), which was later quantified as the Kennicutt-Schmidt law (4). This subsequent model provided the earliest framework of the relationship between large-scale areas of gas accumulation and stellar birth rates. Even now, these laws remain essential for interpreting star formation (5-6).

Reaching more specific levels, like that of stellar populations, there have been several studies that developed stellar population synthesis models, such as (7), which mentioned systematic connections between the key points of this literature review, namely, stellar evolution, metallicity, and observable galaxy spectra. Alongside detailed formulations of the stellar IMF, most notably those of (6, 8) and (11), these models established a system for predicting and forecasting mass-to-light ratios, chemical yields, as well as dynamical feedback from stellar systems.

On the cosmological level, subsequent models refined the trend of star formation. For instance, the work of (10) synthesized observations of the present "cosmic star formation history" and described the rise and fall trend of global star formation throughout time. Another instance is the work of (9), which highlighted the need for metallicity-dependent variations in the IMF, particularly during early star formation. Building off of each other, these studies formed the fundamental backbone of modern star formation theory and established that the IMF, gas conversion efficiency into stars, and environmental metallicity are linked.

MASS-METALLICITY RELATIONSHIP & KEY OBSERVATIONAL EVIDENCE

Through the lens of the James Webb Telescope, an understanding of the observed mass-metallicity relationship (MZR, since metallicity is commonly referred to by the variable Z) could be achieved. Using surveys such as JADES, CEERS, UNCOVER, and several simulations and models, it was established that massive galaxies have proportionally higher stellar metallicities (12-15). The relationship between gas accretion, star formation, outflows, and mergers influences the growth of a galaxy, as well as its metallicity. This growth allows for the mass-metallicity relation, the correlation between gas-phase metallicity and stellar mass in galaxies (15-19). On the other hand, Langeroodi deduced that " results show a clear redshift evolution in the overall normalization of the relation, galaxies at higher redshift having significantly lower metallicities at a given mass (20)." That is, to say that while it may be the case that higher stellar metallicity galaxies tend to be more massive in comparison to a lower stellar metallicity galaxy, it is not a relationship that is clear-cut. In fact, Langeroodi goes on to state that "it has been suggested that the MZR is a two-dimensional representation of a deeper three-dimensional relationship that connects stellar mass, gas-phase metallicity, and the instantaneous SFR, known as the fundamental metallicity relation (20-22)," disproving the universality of the MZR when trying to interpret more complex relationships at a higher redshift.

Another layer of complexity emerges from the FMR, which links stellar mass, gas-phase metallicity, and star formation rate (23). While this three-dimensional framework can explain observed scatter in some instances, its applicability at $z > 3$ remains debated. For example, some studies find that high-redshift galaxies often deviate from the FMR, indicating that additional processes, such as feedback strength or inflow metallicity, may have had the strongest influence in the early universe (13, 24-28). Furthermore, low-mass galaxies at high redshift provide critical constraints on the IMF-metallicity connection.

High-resolution spectroscopy provides spatially resolved metallicity maps, with gradients that show correlations with stellar mass density and recent star formation (19, 29-31). The combination of low metallicity, high star formation rates, and weak gravitational potential in these systems creates environments that favor increased stellar mass (23, 32, 33). These observations underscore the importance of direct measurements of multiple factors in IMF predictions. However, it should be noted that observational challenges remain, especially the uncertainties in metallicity diagnostics.

The use of spectroscopy provides metallicities for very large stellar samples (34, 35), while the use of surveys reveals the chemistry of stellar streams, which is useful because these systems reveal the earlier history of metallicity enrichment (36-39). These works show that the early history of enrichment is often missing details, or better said, patchy. For example, low-metallicity populations and more enriched components can coexist within the same accreted system (40-42). These constraints inevitably complicate MZR trends derived from those systems in particular. Mass is undoubtedly a major factor, but accretion history, feedback, and mixing efficiency produce strong variations between objects (43, 44). Coordinated programs that combine JWST/ALMA spectroscopy, population models that incorporate realistic rotational physics, and testing at different redshifts are essential methods to solving this common problem (45-49).

INITIAL MASS FUNCTION

The IMF remains a fundamental tool for characterizing stellar populations, being able to describe the distribution of stellar masses at birth. Its potential dependence on metallicity has profound consequences for star formation theory and galaxy evolution. In low metallicity environments, dust elevates gas temperatures, increasing the Jeans mass (the minimum mass a gas cloud must have to overcome its internal thermal pressure and collapse under its own gravity, leading to star formation) and favors the formation of more massive stars (50-52). Stellar evolution and winds are themselves dependent on metallicity, which is represented as feedback in IMF simulations and models (53).

Simulation studies broadly support this trend, yet highlight significant complexities. One study found that fragmentation is suppressed in low metallicity clouds, increasing stellar mass (54, 55). Other studies emphasize that feedback interactions with metallicity that influence fragmentation efficiency and cooling physics lead to environment-dependent IMF variations (55-57). Building on the previous idea, local turbulence, magnetic fields, and accretion history can compete with metallicity as a determining factor of stellar mass. These findings imply that a simple metallicity-IMF relationship is an insufficient interpretation, and the interplay between numerous physical factors must be considered (58-64).

In some studies, JWST nebular spectroscopy was used to infer non-universal IMFs in high redshift galaxies, suggesting that heavier stars are more prominent in low metallicity systems (65, 66).

Conversely, bottom-light IMFs in massive star clusters have been identified in clusters that are not lacking in metallicity, which implies that density and environmental factors are more significant compared to metallicity (67-70). It should also be cautioned that simplified star formation history and assumptions to reduce these simplicities in simulations end up complicating IMF inferences, underscoring the need for comprehensive datasets and better diagnostics (71). Furthermore, treating IMF with universality risks overlooking other factors that contribute to results (72).

A critical debate centers on the amplitude of IMF variations at low metallicity. Some simulations suggest only modest shifts in mass, arguing that environmental physics is more significant compared to fragmentation (51). Other simulations predict extreme top heaviness in IMFs in the earlier, lower metallicity systems, also implying high redshift galaxy luminosities, which correlates with an overall higher stellar mass (73, 74). These disagreements highlight the urgent need for coordinated observational and theoretical studies to impose varying metallicity conditions on the IMF, including various inputs that would more than likely improve the accuracy of model results (60, 75).

POPULATION III STARS

Population III Stars, believed to be the very first generation of stars, formed from metal-free gas, which is why they offer an extreme test case as an exception to the usual significance that metallicity has on star formation. Born in an environment devoid of metal, they relied on molecular hydrogen and collision-induced cooling, which results in hotter and higher Jeans mass clouds that tend to form more massive stars. In some cases, they may have also relied on deuterium hydride (76-78). This fundamental difference in formation raises many questions about their IMF. For example, were they exclusively massive, or was there another pathway toward fragmentation and being low to medium-mass stars?

The first three-dimensional simulations of primordial star formation suggested that Pop III stars were extremely massive, often exceeding 100 $M_\odot$, due to inefficient cooling as a byproduct of the absence of metals and dust (76, 77). In this scenario, the primordial IMF was top-heavy (6, 8), and later works reinforced the view of cooling and fragmentation playing a central role (79, 80).

However, studies started to challenge this view, specifically the assumption of pure reliance on hydrogen. It was demonstrated that disk fragmentation around the first proto stars could lead to multiple stellar systems, rather than just massive stars (81). This suggested that the Population III IMF may have been broader than previously assumed, including not only massive stars, but also less massive ones too.

Star-by-star cosmological simulations have also highlighted the role of early chemical enrichment in shaping subsequent IMF variations (82), providing a more resolved view than bulk population models.

One major theoretical milestone was the proposal of a “critical metallicity” threshold, where fragmentation is suppressed and the IMF remains top-heavy (77, 78, 83). Another layer of complexity comes from stellar feedback. For example, radiative and mechanical feedback from Population III stars can heavily influence star formation, whether stimulating or suppressing it

(84, 85). Simulations suggest that enrichment by the first supernovae was inhomogeneous, creating areas of low metallicity gas where Population III stars could form alongside the next generation of Population II stars (86, 87). This suggestion was further developed, moving towards the idea that early galaxies likely hosted overlapping populations, which blurs the line between an era purely comprised of Population III stars and later generations (88, 89).

Multiplicity is another area of uncertainty. Fragmentation could produce binary or multiple stellar systems, broadening the Population III IMF toward lower masses (81, 90, 91). In contrast, simulations predict otherwise for mass. While one study found a wide distribution for a few tens to several hundred solar masses depending on halo properties (90), others predict primarily high mass outcomes. This disagreement illustrates the difficulty in understanding the relationship between fragmentation physics and star formation.

Overall, the literature reveals a field still divided: some models point toward predominantly massive Population III stars that quickly enriched the intergalactic medium, while others allow for a mixed IMF that included longer-lasting and less massive stars. Referring back to Table 1, we can see a trend toward top-heavy IMFs at extremely low metallicities, which aligns with theoretical expectations for Population III stars. However, the disagreement in models shows a constraint that the table may be unable to resolve. Furthermore, the discovery of extremely low metallicity stars in the Milky Way halo illustrates observational constraints (92, 93), but the direct detection of Population III stars still remains difficult.

Hopefully, JWST and newer telescopes will soon provide empirical tests to complete these theories and address these difficulties.

CONCERNS AND LIMITATIONS

Although observations, simulations, systems, and models suggest a relationship between metallicity and stellar mass, important conditions should be considered. The most significant counterexample is the formation of Population III stars, representing the earliest generation of stars in our universe. The fact that these stars formed from gases without metals proves that their mass was not at all influenced by metallicity whatsoever (76, 78). Instead, their large masses seem to be driven by cooling inefficiencies and the behavior of primordial gas clouds, due to the absence of chemical enrichment (80, 90). While metallicity could be a partly determining factor, it should not be considered the only factor in stellar mass.

Even within later generations, there remain several uncertainties that complicate the full picture. For example, observational constraints on IMFs at high redshifts are still prominent due to the difficulty of resolving faint galaxies (18, 94). There also lies the issue of variations in IMF slopes, which could be due to a number of reasons, such as selection biases and uncertainties within the models themselves. Some theoretical works argue that turbulence, magnetic fields, and feedback play roles comparable to or exceeding the role that metallicity plays in shaping stellar masses (50, 51).

Another limitation is the inability to isolate the influence of metallicity from that of other parameters. For example, galaxy mass, star formation rate, and

Table 1. Comparative summary of the relationship among metallicity, fragmentation, and IMF predictions across different studies

Metallicity Regime	Dominant Physical Process	Predicted IMF Trend	Key References
Primordial / $Z \approx 0$ (Population III)	H_2 and HD cooling; inefficient dust cooling; high gas temperatures; limited fragmentation	Top-heavy IMF; massive ($> 100\ M_\odot$) stars favored	(76, 77, 90, 93)
Very Low Metallicity ($Z < 10^{-3}\ Z_\odot$)	Onset of dust cooling and disk fragmentation; partial molecular cooling	Moderately top-heavy IMF; mixture of massive and intermediate-mass stars	(80, 83, 84)
Low – Intermediate Metallicity ($10^{-3}\ Z_\odot < Z < Z_\odot$)	Efficient metal and dust cooling; enhanced fragmentation efficiency	Near-Salpeter IMF; modest metallicity dependence	(6, 8, 58, 60)
Solar – Super-Solar Metallicity ($Z \approx Z_\odot – 2\ Z_\odot$)	Strong stellar winds and feedback; radiation pressure limits massive-star growth	Bottom-heavier IMF; low-mass stars favored	(67, 69, 75)

environment all evolve simultaneously with metallicity, and they all play interdependent roles that cannot be separated distinctly (13, 49). This makes it challenging to untangle whether observed IMF variations are caused by metallicity itself or by other underlying processes. Addressing this requires larger samples, deeper high-redshift observations, and more sophisticated simulations that can separately vary metallicity while controlling other parameters.

There also lies a certain methodological uncertainty in the measurements, models, and simulations of metallicity measurements. The reason for this uncertainty in measurement is attributed to the fact that each study that conducts research and records data likely has unique calibration settings, making it impossible to ascertain an absolute conclusion about measurements. As a consequence, IMF inferences can't be treated as absolute by extension, though it doesn't entirely disprove the findings.

In short, while metallicity is an important variable, its influence on stellar masses may not be universal. The existence of Population III stars reminds us that metallicity's role likely depends on cosmic time and environmental context.

CONCLUSION

The relationship between metallicity and stellar mass formation remains one of the most critical questions in astrophysics. On the one hand, substantial observational evidence points to a correlation between chemical enrichment and IMF variation, particularly in low-metallicity galaxies and early-universe environments (95). On the other hand, the existence of Population III stars demonstrates that metallicity cannot be the sole factor in stellar masses, especially under specific primordial conditions.

Future progress will depend on connecting theoretical predictions and empirical data. Improved stellar population synthesis models, high-resolution simulations, and deep surveys with instruments like JWST will allow researchers to test whether IMF variations are consistent across environments or whether other factors take precedence in certain regimes. As summarized in Table 1, metallicity influences stellar fragmentation and IMF behavior in systematic but non-exclusive ways, with additional dependencies on feedback, turbulence, and environment.

In conclusion, metallicity plays a central but not exclusive role in the determination of stellar mass. By considering counterexamples such as Population III stars and systematically testing alternative explanations, we can move toward a more complete theory of how the IMF emerges across cosmic history.

CONFLICT OF INTERESTS

The author(s) declares that there are no conflicts of interests related to this work.

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