Metallicity - Population III Stars - JWST

Definition of Metallicity, Z:

The relative abundances of the chemical elements can be measured in a number of astronomical objects, in particular using spectroscopic techniques. **The observed strengths of spectral lines** depend on a variety of factors among which are the chemical abundances of the elements producing those spectral lines.
It is convenient to define the fractions by mass of hydrogen X, of helium Y, and of heavy elements Z.
Therefore, Z = (mass of heavy elements)/(total mass of all nuclei). in some object, objects or region of space. We therefore have $X + Y + Z \equiv 1$.

The most recent determination of the solar $Z(Z_\odot)$ gives a value of 0.0134.

A very small fraction of metals is sufficient to alter the behavior of the star completely.

The more metallic a star, the more opaque it is (since metals absorb radiation), and how opaque it is, in turn, relate to its size, temperature, brightness, life span, and other key properties. Metallicity basically also tells you how the star will die.

Population III Stars

The advancement of observational technologies has brought increasing attention to the study of the first galaxies, black holes, and stars in the early universe. Detection of population III stars is a goal of NASA's James Webb Space Telescope. Among its many grand discoveries set to come, perhaps the greatest of all is the possibility of observing the light from the very first stars in the Universe. These **chemically pristine**, so-called '**Population III'** stars, formed out of the primordial hydrogen and helium (and trace amounts of lithium), and were the first embers to ignite, producers of the starlight that ended the cosmic dark ages and paved the way for cosmic dawn.

Sirius is the star with the highest known metallicity of 0.5, which corresponds to a Fe to H ratio of three times the sun. The search of Population III stars with JWST is actively ongoing. The search is for strongly-lensed extremely metal-poor small mass star clusters of $10^4\ M_\odot$ and with $Z \sim 10^{-3}\ Z_\odot$.

The Simple Model of Galactic Chemical Evolution

$M_{total} = M_{stars} + M_{gas}$ Therefore the heavy element mass fraction of the gas is

$$Z \equiv \frac{M_{\rm metals}}{M_{\rm gas}}$$

Let the change in M_{stars} and M_{gas} in this time be δM_{stars} and δM_{gas}.
We firstly need to express the change δZ in the metallicity of the interstellar gas in terms of δM_{stars} and δM_g

$$\delta Z = \frac{\delta M_{\rm metals}}{M_{\rm gas}} - Z\frac{\delta M_{\rm gas}}{M_{\rm gas}}$$

We need to distinguish between the the total mass in stars M_{stars} at time t and the total mass that has taken part in **star formation** M_{SF} over all periods up to time t. When a mass δM_{SF} goes into stars during star formation, the total mass in stars will change by amount less than this, because material from the new stars is ejected back into the interstellar gas. So, $\delta M_{SF} > \delta M_{stars}$, and $M_{SF} > M_{stars}$.
Let α be the fraction of mass participating in star formation that remains locked up in long-lived stars (and stellar remnants). So, $\delta M_{stars} = \alpha\, \delta M_{SF}$ (with $0 < \alpha < 1$)
The mass of newly synthesized heavy elements ejected back into the Interstellar Medium, ISM, is proportional to the mass that goes into stars (from the Simple Model assumptions listed above). Let the mass of newly synthesized heavy elements ejected into the ISM be equal to $p\,\delta M_{stars}$, where p is a parameter known as the yield, with p set to be a constant here. This gives

$$Z(t) = -p\ \ln\left(\frac{M_{\rm gas}(t)}{M_{\rm gas}(0)}\right)$$

Since the $M_{gas}(0) = M_{total}(t)$ (a constant) for all t (because we have a closed box that initially contained only gas), we can rewrite this equation using the gas fraction $\mu \equiv M_{gas}(t)/M_{total}(t)$ as $Z(t) = -p \ln \mu$

$$Z = -p \ln\left(\frac{M_{\text{gas}}(0) - M_{\text{stars}}(t)}{M_{\text{gas}}(0)}\right) \text{ which rearramges to } \frac{M_{\text{stars}}(t)}{M_{\text{gas}}(0)} = 1 - e^{-Z(t)/}$$

This is a prediction of how the fraction of the mass of the volume that is in stars varies with metallicity. $M_{stars}(t)/M_{gas}(0)$ increases from zero at time t = 0, and can become very large if most of the gas is used up in star formation. Today, at time t_1 , we have a metallicity Z_1 and a mass in stars M_{stars1} . Therefore we have

$$\frac{M_{\text{stars}}(t)}{M_{\text{stars1}}} = \frac{1 - e^{-Z(t)/p}}{1 - e^{-Z_1/p}} \qquad \frac{N(Z)}{N_1} = \frac{1 - e^{-Z(t)/p}}{1 - e^{-Z_1/p}}$$

where N_1 is the value of N(Z) today.

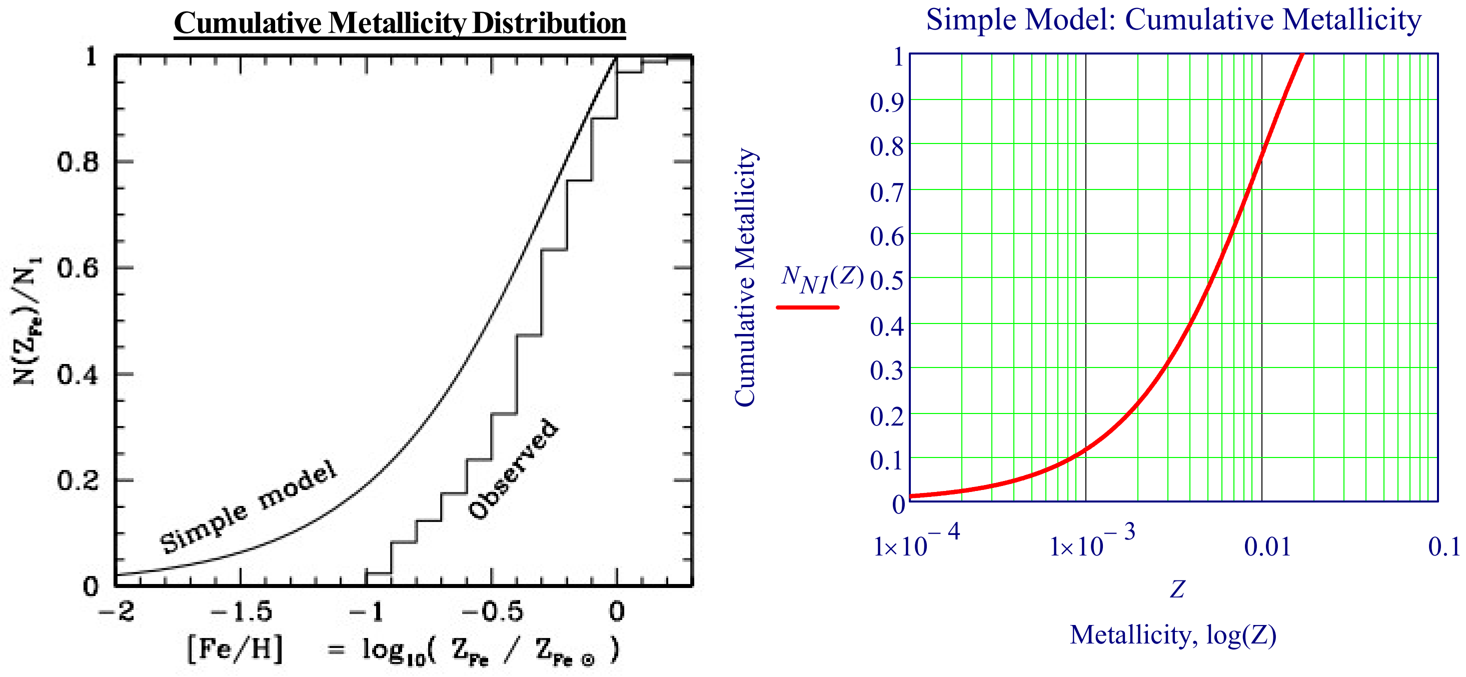
This gives a specific prediction of the number of stars as a function of metallicity

The figure below gives a comparison of the the predicted metallicity distribution from Equation N(Z) with observations of long-lived stars in the solar neighbourhood. The Simple Model prediction is found to be very different to the observed distribution.

The Simple Model predicts a far larger proportion of Metal-Poor Stars than are actuall found.
This has become known as the G dwarf problem.

$$p := 0.010 \qquad Z_1 := 0.017 \qquad \frac{N(Z)}{N_1} = \frac{1 - e^{-Z(t)/p}}{1 - e^{-Z_1/p}} \qquad N_{N1}(Z) := \frac{1 - exp\left(\frac{-Z}{p}\right)}{1 - exp\left(\frac{-Z_1}{p}\right)}$$

The observed iron abundance, [Fe/H], is often regarded as a proxy for the total metallicity, Z, of stars.



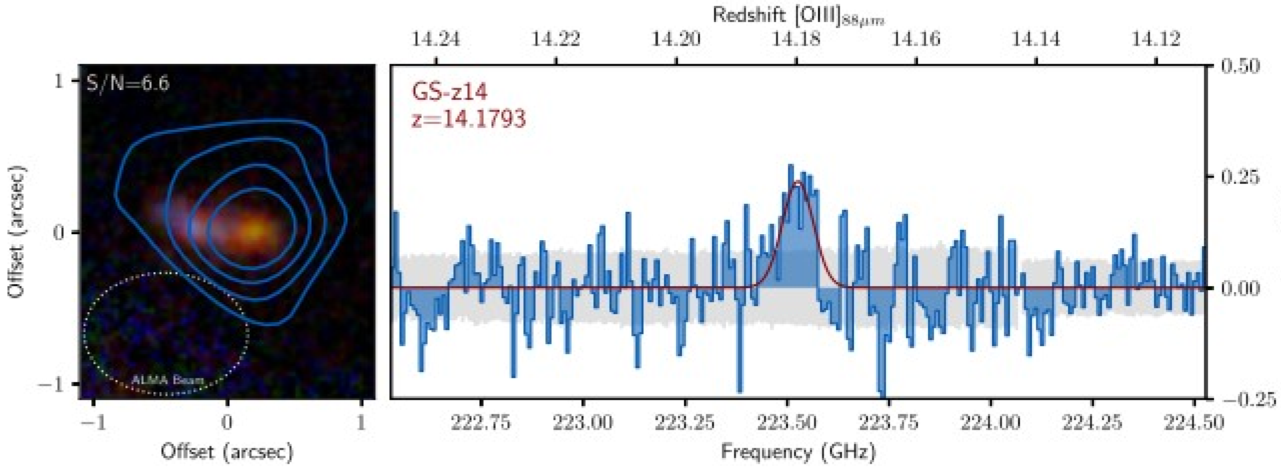
The observed **Cumulative Metallicity** distribution for stars in the solar neighbourhood, compared with the Simple Model prediction for p = 0.010 and $Z_1 = Z_\odot = 0.017$.

[The observed distribution uses data from Kotoneva et al.,M.R.AS, 336, 879, 2002, for stars in the Hipparcos Catalog.]

Population III Stars Metallicity- JWST - Continued

Contrary to Expectations: Metallicity and Mass

JWST found young stars that are hotter and with high metallicity. Some where found with nickel, which is heavier than iron in the periodic table. This came as somewhat of a surprise. The JWST observation of the galaxy **JADES-GS-z14-0** at redshift z=14.32, which is the most distant galaxy observed, shows surprisingly high metal enrichment (**$Z \sim 0.05 - 0.2\, Z_\odot$**), indicating a rapid assembly of metals in the early universe and it started galaxy formation very early. It is 325 to 330 million years old (2.1% of Universe Age.) It is also far more massive than expected, $M \sim 500\ 10^6\ M_\odot$.



JADES-GS-z14-0 Atacama Large Millimeter/submillimeter Array (**ALMA**), **found an emission line of oxygen**, making this the most distant detection of oxygen, when the Universe was slightly under a mere 300 million years old. *Detection of [OIII] 88μm in JADES-GS-z14-0 at z=14.1793,* S. Schouws et. all, March 17, 2025, www.eso.org/public/

Under current cosmological models, all matter created in the Big Bang was mostly hydrogen (75%) and helium (25%), with only a very tiny fraction consisting of other light elements such as lithium and beryllium.

When the universe had cooled sufficiently, the first stars were born as population III stars, without any contaminating heavier metals. This is postulated to have affected their structure so that their stellar masses became hundreds of times more than that of the Sun. In turn, these massive stars also evolved very quickly, and their nucleosynthetic processes created the first 26 elements (up to iron in the periodic table). Many theoretical stellar models show that most high-mass population III stars rapidly exhausted their fuel and likely exploded in extremely energetic pair-instability supernovae. The oldest stars observed thus far, **known as population II, have very low metallicities**; as subsequent generations of stars were born, they became more metal-enriched, as the gaseous clouds from which they formed received the metal-rich dust manufactured by previous generations of stars from population III.
As those population II stars died, they returned metal-enriched material to the interstellar medium via planetary nebulae and supernovae, enriching further the nebulae, out of which the newer stars formed.

These youngest stars, including the Sun, therefore have the **highest metal content,** known as **population I stars**.

Required JWST Instrumentation

Requires ultradeep exposures would be needed to detect ~ $10^5\ M_\odot$ Pop III galaxies at z = 10, with color–colour selections combining JWST/NIR Cam and JWST/MIRI photometry enabling a clean selection of Pop III galaxies at z ≈ 7–8. Fortuitous gravitational Lansing of Pop III galaxies will greatly relax the otherwise demanding integration times needed.
See Section XXIV: Advances in Measurement and Technology for Measuring Hubble Constant

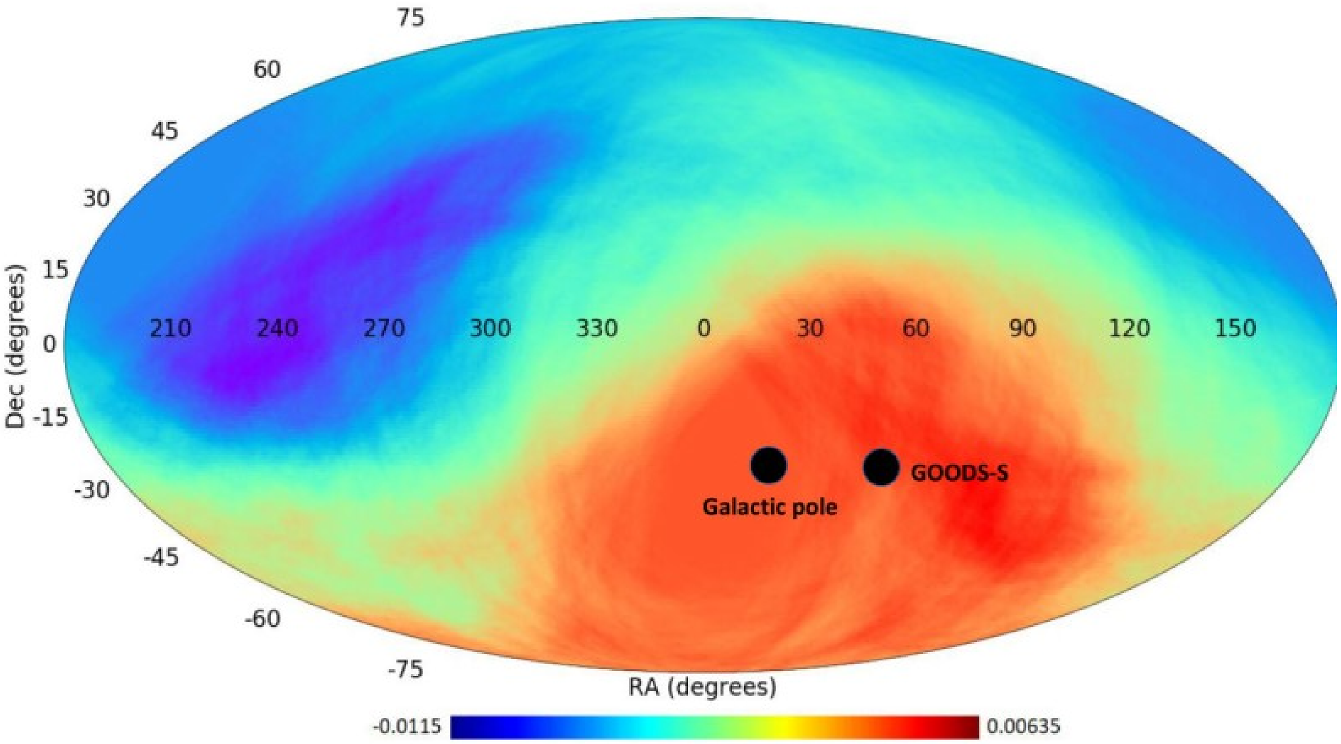
Some Possible Explanations

Any one or combination of these proposed explanations appears feasible: (1) a higher star formation efficiency at that time; (2) a higher percentage of very massive stars at that time; (3) a reduced quantity of dust or the presence of dust with a less dimming effect; and (4) adjustments to our understanding of the properties of dark matter haloes at that time. Spectroscopic follow-up studies for the observed galaxy candidates are ongoing. As research continues, the list of 90 ultrabright galaxies initially thought to have formed early in the cosmic dawn will likely be reduced.

Distribution of Galaxy Rotation in JWST Advanced Deep Extragalactic Survey

The distribution of galaxy rotation in JWST Advanced Deep Extragalactic Survey, Lior Shamir,
MNRAS 538, 76–91 (2025) https://doi.org/10.1093/mnras/staf292

Analysis of spiral galaxies by their direction of rotation in JADES
shows that the number of galaxies in that field that rotate in the opposite direction relative to the Milky Way galaxy is ~ 50 per cent higher than the number of galaxies that rotate in the same direction relative to the Milky Way. The analysis is done using a computer-aided quantitative method, but the difference is so extreme that it can be noticed and inspected even by the unaided human eye. These observations are in excellent agreement with deep fields taken at around the same footprint by Hubble Space Telescope and JWST.



The differences in the number of galaxies with opposite directions of rotations in different parts of the sky as determined by using 1.3 × 10^6 galaxies imaged by the DESI Legacy Survey (Shamir 2022e).
The location of the GOODS-S field is at a part of the sky with a higher number of galaxies rotating clockwise.

Redshift z	**cw**	**ccw**	**cw/cw+ccw**	**p-value**
0 - 0.05	3216	3180	0.5003	0.698
0.05 - 0.1	6240	6270	0.498	0.4
0.1 - 0.15	4236	4273	0.496	0.285
0.15 - 0.2	1586	1716	0.479	0.008
0.2 - 0.5	2598	2952	0.469	1.07×10^{-6}
Total	17876	18391	0.493	0.0034

As the above table shows, the asymmetry increases as the redshift gets higher.

The distribution of galaxies rotating clockwise and counterclockwise imaged by SDSS. All galaxies are within the RA range of (120°, 210°). The p-values are the binomial distribution p-value to have such asymmetry or stronger by chance. The table is taken from Shamir (2020) springer.com/article/10.1007/s10509-020-03850-1