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Earth's Oxygenation History - One Key to Unlocking Exoplanetary Habitability

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Essay Description

The Earth's oxygenation history is a complex chain of events occurring over billions of years. The atmosphere has been shaped by both biological and geological transformations, with life evolving alongside these changes. During the Archean geological eon, Earth's atmosphere had negligible atmospheric concentrations of oxygen, before the photosynthetic activity of cyanobacteria combined with hydrogen escape, gave rise to the Great Oxidation Event. This occurred approximately 2.4 billion years ago and marked the start of the Proterozoic geological eon. Following this milestone, the Earth endured a protracted period known as the "Boring Billion," characterised by relatively stable and warm geological conditions. The Neoproterozoic Oxygenation Event, roughly 850 to 540 million years ago, ushered in another significant rise in oxygen levels. This coincided with the emergence and diversification of complex multicellular life forms and was followed by the Cambrian explosion, which witnessed the rapid proliferation of animal phyla.

When assessing the habitability of Earth-like exoplanets, it is sensible to turn to Earth's own history as a benchmark. How the oxygenation timeline correlates with the emergence and sustenance of complex life is uncertain. However, the presence of atmospheric oxygen on a planetary scale is crucial in determining habitability, as it gives rise to the ozone layer, which blocks harmful ultraviolet radiation from reaching the surface. Earth's journey from an anoxic environment to one abundant in oxygen provides valuable insights into the interplay between geological processes, atmospheric composition, and the evolution of life, serving as a reference point for evaluating the potential habitability of distant exoplanets. When future observations of Earth-like exoplanets are made, how astronomers interpret the observed transmission spectra and direct-imaging spectra will be key to determining if any worlds are habitable, and indeed, inhabited.

This essay should summarise the current state of knowledge regarding Earth’s oxygenated history and highlight the major events that transformed the biosphere. It should discuss the significance of Earth's oxygenation history as a foundation for discerning the conditions necessary for life to flourish on distant worlds. Additionally, it should explore various observational techniques employed by astronomers to identify the presence of oxygen and other potential biosignatures in the atmospheres of terrestrial exoplanets, ultimately commenting on the reliability of any future conclusions that may be reached regarding the possible presence of extraterrestrial life.

Useful References

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Cosmology with Fast Radio Bursts (FRBs)

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Essay Description

Fast radio bursts (FRBs), transient radio signals of yet-unestablished nature, may prove to be new and unique cosmological probes, thus complementing the picture of the Universe that we draw based on the measurements of the cosmic microwave background (CMB) and surveys of the nearby cosmos.

FRBs are narrow pulses of radio signals, which are significantly dispersed by the ionized medium distributed along the path between the source and the observer. For most of the detected FRBs, the observed dispersion of FRB pulses, quantified in terms of dispersion measure (DM), is much larger than the contribution of our local environment. Therefore, it is now known that the overwhelming majority of FRBs are of extragalactic origin.

By exploring the dependence of DM on the cosmological redshift, one can extract information about the composition of the underlying Universe and probe its expansion history. At low redshifts, FRBs have already proven to be valuable cosmological probes. It has been shown that dependence of DM on the cosmological redshift, z, of the FRB hosts could pin down properties of the intergalactic medium (IGM) and probe cosmological parameters. To give an example, with a sample of localized low-redshift FRBs (host redshifts of $z < 0.66$), Macquart et al. (2020) showed that the dispersion measure of these transients depends on the baryonic content of the Universe (along the line of sight) and, thus, can help identifying the missing baryons in the IGM by counting the total number of baryons along the line of sight. For higher redshift FRBs, beyond the current observational cut-off of z~3, theoretical predictions show that a population of FRBs at z = 3–4 could be used to constrain helium reionization occurring around redshift z~3.5, while signals from $z > 5$ would primarily trace the evolution of the hydrogen ionization state, and, thus, probe the epoch of reionization.

The goal of this project is to review the status of the field and explore FRBs as cosmological probes at low and high redshifts.

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From Cosmic Bursts to Galactic Disks: Linking High-Redshift JWST Observations and Clues from the Milky Way

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Essay Description

Thanks to direct lookback observations with the James Webb Space Telescope and archaeological studies of the Milky Way using old, metal-poor stars, we have recently obtained surprising new insights into the formation and evolution of galaxies in the early Universe.

For instance, we observe that, unlike their counterparts in the local Universe, high-redshift galaxies undergo stochastic star formation. This means that the conversion of gas into stars proceeds discontinuously, with intense bursts of activity followed by pronounced quiescent phases. Direct evidence for this stochastic star formation comes from both spectroscopic observations and the modeling of broadband photometry from JWST. Burstiness is demonstrated through studies of, for example, emission line indicators of the current star formation rate and UV fluxes, which are sensitive to longer-term star formation behavior. The burstiness increases with redshift and decreases with galaxy luminosity. Notably, models incorporating stochastic star formation explain the excess of UV-luminous galaxies at high redshifts. These models predict that the UV luminosity function will change shape and extend to higher luminosities due to the up-scattering of low-mass objects—observational hints of both phenomena may already have been found.

Burstiness also appears to be linked to morphological characteristics. Numerical simulations indicate that galaxies experiencing strong variations in star formation activity exhibit messy, unstructured, and chaotic stellar distributions. Observationally, this is supported by images of high-redshift galaxies, which appear blobby and asymmetric, suggesting a lack of coherence. As galaxies build up their mass, star formation becomes more orderly, and large jumps in the star formation rate subside. This transition is accompanied by the emergence of a stable, coherently rotating stellar disk. The exact details of the physical processes leading to disk formation remain unclear, as many key mechanisms (e.g., related to stellar feedback) are still modeled using sub-grid recipes. Observational evidence is also mixed: while high-redshift gas disks have been detected, tracking the formation of stellar disks remains a challenge.

The Milky Way provides a unique, high-resolution window into the physics governing structure formation in the early Universe. By using the chemical and orbital properties of old, relatively metal-poor stars, it has been possible to scrutinize the epochs directly before our Galaxy managed to “spin up”—that is, to form a stable stellar disk. These primordial stellar populations exhibit large scatter in chemical abundances, which later decreases significantly in sync with the appearance of coherent rotation. Through comparison with so-called zoom-in simulations, this has been interpreted as strong evidence for a chaotic, turbulent pre-disk state of the Galaxy. While the transformation from a disordered, bursty pre-disk state to a stable, fast-rotating stellar disk is ubiquitous across simulations, numerical models tend to form stellar disks later than observed in the Milky Way.

The observed chemical spreads in the early Milky Way may result from a significant contribution by massive bound star clusters, analogous to globular clusters. Evidence for this comes from the large proportion of nitrogen-rich stars in the pre-disk population of the Galaxy. Locally, such anomalously high nitrogen levels are only seen in second-generation stars born in globular clusters. Note that curiously, several high-redshift galaxies exhibit equally strong nitrogen over-abundance but in nebular emission from the gas surrounding young stars. Reconstructing the globular cluster-born populations from these nitrogen-rich stars suggests that as much as half of the total stellar mass of the young Milky Way could have formed inside massive clusters. This is unsurprising, given that the extreme conditions at high redshift—such as lumpy gas density distributions with high-amplitude variations and strong radiation fields—are much more conducive to massive cluster formation than the quiet and stable conditions of the local Universe. It remains extremely challenging to resolve early galaxies sufficiently to observe individual star clusters, but recently, with the aid of gravitational lensing, we have been able to peer inside a typical z=8 galaxy, which appeared to be composed of massive balls of light, resembling the high-redshift counterparts of Galactic globular clusters.

This essay should examine current observational evidence from both high-redshift galaxies observed by JWST and local observations of the Milky Way. By comparing and contrasting these observations, and focusing on the connection between globular clusters, star formation burstiness, and disk formation, the essay should shed light on the processes that shaped the early evolution of the Milky Way and progenitor galaxies of similar mass.

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- "Stochastic star formation and the abundance of $z>10$ UV-bright galaxies" by Kravtsov et al (URL)
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- "Galactic Archaeology with Gaia" by Deason et al (URL)