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The habitable epoch of the early Universe

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Abstract: In the redshift range $100 \lesssim (1+z) \lesssim 137$, the cosmic microwave background (CMB) had a temperature of 273–373 K (0–100 °C), allowing early rocky planets (if any existed) to have liquid water chemistry on their surface and be habitable, irrespective of their distance from a star. In the standard ΛCDM cosmology, the first star-forming halos within our Hubble volume started collapsing at these redshifts, allowing the chemistry of life to possibly begin when the Universe was merely 10–17 million years old. The possibility of life starting when the average matter density was a million times bigger than it is today is not in agreement with the anthropic explanation for the low value of the cosmological constant.

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Introduction

The habitable zone is commonly defined in reference to a distance from a luminous source, such as a star (Kasting *et al.* 1993; Kasting 2010), whose heat maintains the surface of a rocky planet at a temperature of ~ 300 K, allowing liquid water to exist and the chemistry of 'life as we know it' to operate. In this brief paper, I point out that the cosmic microwave background (CMB) provided a uniform heating source at a temperature of $T_{\rm cmb} = 272.6\,{\rm K} \times [(1+z)/100]$ (Fixsen 2009) that could have made by itself rocky planets habitable at redshifts $(1+z) = 100$–137 in the early Universe, merely 10–17 million years after the Big Bang.

In order for rocky planets to exist at these early times, massive stars with tens to hundreds of solar masses, whose lifetime is much shorter than the age of the Universe, had to form and enrich the primordial gas with heavy elements through winds and supernova explosions (Ober *et al.* 1983; Heger & Woosley 2002). Indeed, numerical simulations predict that predominantly massive stars have formed in the first halos of dark matter to collapse (Bromm & Larson 2004; Loeb & Furlanetto 2012). For massive stars that are dominated by radiation pressure and shine near their Eddington luminosity $L_{\rm E} = 1.3 \times 10\,{\rm erg\,s^{-1}}(M_*/100\,M_\odot)$, the lifetime is independent of the stellar mass M_* and set by the 0.7% nuclear efficiency for converting the rest mass to radiation, $\sim (0.007\,M_* c^2)/L_{\rm E} = 3$ Myr (El Eid *et al.* 1983; Bromm *et al.* 2001; Marigo *et al.* 2003). We next examine how early such stars formed within the observable volume of our Universe.

First planets

In the standard cosmological model, structures form hierarchically – starting from small spatial scales, through the gravitational growth of primordial density perturbations (Loeb & Furlanetto 2012). On any given spatial scale R, the probability distribution of fractional density fluctuations δ is assumed to have a Gaussian form, $P(\delta)d\delta = (2\pi\sigma^2)^{-1/2}\exp\{-\delta^2/2\sigma^2\}d\delta$, with a root-mean-square amplitude $\sigma(R)$ that is initially much smaller than unity. The initial $\sigma(R)$ is tightly constrained on large scales, $R \gtrsim 1$ Mpc, through observations of the CMB anisotropies and galaxy surveys (Ade *et al.* 2013a; Anderson *et al.* 2014), and is extrapolated theoretically to smaller scales. Throughout the paper, we normalize spatial scales to their so-called 'comoving' values in the present-day Universe. The assumed Gaussian shape of $P(\delta)$ has so far been tested only on scales $R \gtrsim 1$ Mpc for $\delta \lesssim 3\sigma$ (Shandera *et al.* 2013), but was not verified in the far tail of the distribution or on small scales that are first to collapse in the early Universe.

As the density in a given region rises above the background level, the matter in it detaches from the Hubble expansion and eventually collapses owing to its self-gravity to make a gravitationally bound (virialized) object like a galaxy. The abundance of regions that collapse and reach virial equilibrium at any given time depends sensitively on both $P(\delta)$ and $\sigma(R)$. Each collapsing region includes a mix of dark matter and ordinary matter (often labelled as 'baryonic'). If the baryonic gas is able to cool below the virial temperature inside the dark matter halo, then it could fragment into dense clumps and make stars.

At redshifts $z \gtrsim 140$ Compton cooling on the CMB is effective on a timescale comparable to the age of the Universe, given the residual fraction of free electrons left over from cosmological recombination (see section 2.2 in Loeb & Furlanetto (2012) and Pritchard & Loeb (2012)). The thermal coupling to the CMB tends to bring the gas temperature to $T_{\rm cmb}$, which at $z \sim 140$ is similar to the temperature floor associated with molecular hydrogen cooling (Haiman *et al.* 1996; Tegmark *et al.* 1997; Hirata & Padmanabhan 2006). In order for virialized gas in a dark matter halo to cool, condense and fragment into stars, the halo virial temperature $T_{\rm vir}$ has to exceed $T_{\rm min} \approx 300$ K, corresponding to $T_{\rm cmb}$ at $(1+z) \sim 110$. This implies a halo mass in excess of $M_{\rm min} = 10^4\,M_\odot$, corresponding to a baryonic mass $M_{\rm b,min} = 1.5 \times 10^3\,M_\odot$, a circular virial velocity $V_{\mathrm{c,min}} = 2.6\,\mathrm{km\,s}^{-1}$ and a virial radius $r_{\mathrm{vir,min}} = 6.3\,\mathrm{pc}$ (see section 3.3 in Loeb & Furlanetto 2012). This value of $M_{\min}$ is close to the minimum halo mass to assemble baryons at that redshift (see section 3.2.1 in Loeb & Furlanetto (2012) and Fig. 2 of Tseliakhovich *et al.* (2011)).

The corresponding number of star-forming halos on our past light cone is given by (Naoz *et al.* 2006),

$$N = \int_{(1+z)=100}^{(1+z)=137} n(M > M_{\min}, z') \frac{\mathrm{d}V}{\mathrm{d}z'} \mathrm{d}z', \qquad (1)$$

where $n(M > M_{\min})$ is the comoving number density of halos with a mass $M > M_{\min}$ (Sheth & Tormen 1999), and $\mathrm{d}V = 4\pi r^2 \mathrm{d}r$ is the comoving volume element with $\mathrm{d}r = c\mathrm{d}t/a(t)$. Here, $a(t) = (1+z)^{-1}$ is the cosmological scale factor at time t, and $r(z) = c\int_0^z \mathrm{d}z'/H(z')$ is the comoving distance. The Hubble parameter for a flat Universe is $H(z) \equiv (\dot{a}/a) = H_0\sqrt{\Omega_m(1+z)^3 + \Omega_r(1+z)^4 + \Omega_\Lambda}$, with Ω_{m}, Ω_{r} and Ω_Λ being the present-day density parameters of matter, radiation and vacuum, respectively. The total number of halos that existed at $(1+z) \sim 100$ within our entire Hubble volume (not restricted to the light cone), $N_{\mathrm{tot}} \equiv n(M > M_{\min}, z = 99) \times (4\pi/3)(3c/H_0)^3$, is larger than N by a factor of $\sim 10^3$.

For the standard cosmological parameters (Ade *et al.* 2013a), we find that the first star-forming halos on our past light cone reached their maximum turnaround radius[1] (with a density contrast of 5.6) at $z \sim 112$ and collapsed (with an average density contrast of 178) at $z \sim 71$. Within the entire Hubble volume, a turnaround at $z \sim 122$ resulted in the first collapse at $z \sim 77$. This result includes the delay by $\Delta z \sim 5.3$ expected from the streaming motion of baryons relative to the dark matter (Fialkov *et al.* 2012).

The above calculation implies that rocky planets could have formed within our Hubble volume by $(1+z) \sim 78$ but not by $(1+z) \sim 110$ if the initial density perturbations were perfectly Gaussian. However, the host halos of the first planets are extremely rare, representing just $\sim 2 \times 10^{-17}$ of the cosmic matter inventory. Since they lie ~ 8.5 standard deviations (σ) away on the exponential tail of the Gaussian probability distribution of the initial density perturbations, $P(\delta)$, their abundance could have been significantly enhanced by primordial non-Gaussianity (LoVerde & Smith 2011; Maio *et al.* 2012; Musso & Sheth 2013) if the decline of $P(\delta)$ at high values of δ/σ is shallower than exponential. The needed level of deviation from Gaussianity is not ruled out by existing datasets (Ade *et al.* 2013b). Non-Gaussianity below the current limits is expected in generic models of cosmic inflation (Maldacena 2003) that are commonly used to explain the initial density perturbations in the Universe.

Discussion

In this brief paper, I highlighted a new regime of habitability made possible for ~ 6.6 Myr by the uniform CMB radiation at redshifts $(1+z) = 100$–137, just when the first generation of star-forming halos (with a virial mass $\gtrsim 10^4\,M_\odot$) turned around in the standard cosmological model with Gaussian initial conditions. Deviations from Gaussianity in the far (8.5σ) tail of the probability distribution of the initial density perturbations could have led already at these redshifts to the birth of massive stars, whose heavy elements triggered the formation of rocky planets with liquid water on their surface.[2]

Thermal gradients are needed for life. These can be supplied by geological variations on the surface of rocky planets. Examples of sources of free energy are geothermal energy powered by the planet's gravitational binding energy at formation and radioactive energy from unstable elements produced by the earliest supernova. These internal heat sources (in addition to possible heating by a nearby star) may have kept planets warm even without the CMB, extending the habitable epoch from $z \sim 100$ to later times. The lower CMB temperature at late times may have allowed ice to form on objects that delivered water to a planet's surface, and helped to maintain the cold trap of water in the planet's stratosphere. Planets could have kept a blanket of molecular hydrogen that maintained their warmth (Stevenson 1999; Pierrehumbert & Gaidos 2011), allowing life to persist on internally warmed planets at late cosmic times. If life persisted at $z \lesssim 100$, it could have been transported to newly formed objects through panspermia (McNichol & Gordon 2012). Under the assumption that interstellar panspermia is plausible, the redshift of $z \sim 100$ can be regarded as the earliest cosmic epoch after which life was possible in our Universe.

The feasibility of life in the early Universe can be tested by searching for planets with atmospheric bio-signatures around low-metallicity stars in the Milky Way galaxy or its dwarf galaxy satellites. Such stars represent the closest analogues to the first generation of stars at early cosmic times.

The possibility that the chemistry of life could have started in our Universe only 10–17 Myr after the Big Bang is not in agreement with the anthropic explanation[3] for the value of the cosmological constant (Weinberg 1987), especially if the characteristic amplitude of the initial density perturbations or the level of non-Gaussianity is allowed to vary in different regions of the multiverse[4] (Garriga & Vilenkin 2006; Tegmark *et al.* 2006). In principle, the habitable cosmological epoch considered here allows for life to emerge in a Universe with a

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[1] In the spherical collapse model, the turnaround time is half the collapse time.

[2] The dynamical time of galaxies is shorter than $\sim 1/\sqrt{200} = 7\%$ of the age of the Universe at any redshift since their average density contrast is $\gtrsim 200$. After the first stars formed, the subsequent delay in producing heavy elements from the first supernovae could have been as short as a few Myr. The supernova ejecta could have produced high-metallicity islands that were not fully mixed with the surrounding primordial gas, leading to efficient formation of rocky planets within them.

[3] In contrast to Weinberg (1987), we require here that stars form in any low-mass halo rather than in a galaxy as massive as the Milky-Way, as the pre-requisite for life.

[4] An increase in the initial amplitude of density perturbations on the mass scale of $10^4\,M_\odot$ by a modest factor of $1.4 \times [(1+z)/110]$ would have enabled star formation within the Hubble volume at redshifts $(1+z) > 110$ even for perfectly Gaussian initial conditions.

cosmological constant that is $(1+z)^3 \sim 10^6$ times bigger than observed (Loeb 2006). If observers can eventually emerge from primitive forms of life at an arbitrarily later time in such a Universe, then their existence would be in conflict with the anthropic reasoning for the low value of the cosmological constant in our Universe. Even when placed on a logarithmic scale, the corresponding discrepancy in the vacuum energy density is substantial, spanning $\sim 5\%$ of the ~ 120 orders of magnitude available up to the Planck density. The volume associated with inflating regions of larger vacuum density is exponentially greater than our region, making residence in them far more likely.

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