Cosmic Engineering

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Abstract

Cosmologists routinely make the assumption that the observed large scale structure in the Universe was shaped by gravity. However, given that the cosmic expansion accelerates, intelligent civilizations which were used to communicating with each other across cosmological distances might have decided to propel themselves closer together so that they would not be pulled apart and lose contact with each other in the distant future due to the accelerated expansion. *Could we identify the related motions or artificial clustering of sources in cosmological data sets?* I show that the power required to move a star at a constant speed across cosmological distances can be supplied by the nuclear energy production in the star. Assuming that a significant fraction of this power is emitted in the infrared, the *James Webb Space Telescope* will be able to detect a single stellar-mass object propelled at a constant speed $v_{\rm p}$ out to a distance of $\sim 10(v_{\rm p}/10^4~{\rm km~s^{-1}})$ Mpc. Detection of the non-gravitational clustering and dynamics of *many* such sources would provide evidence for a new phenomenon of *cosmic engineering*.

I. INTRODUCTION

Cosmological observations imply that the expansion of the Universe has been accelerating over the past 6.5 billion years due to a nearly constant vacuum energy density [1–3]. During that time, widely separated civilizations have been receding away from each other at an ever increasing speed. Only civilizations which are already gravitationally bound to highly nonlinear structures (such as groups or clusters of galaxies) have the prospects of maintaining their community in the future; mildly nonlinear superclusters, such as the prominent Shapley supercluster, will be torn apart by the cosmic acceleration [4]. Closer to home, our own Milky Way galaxy will be separated from the nearby Virgo cluster and will only stay bound to the Local Group [5].

If the vacuum density stays constant (as expected in the standard cosmological model or in the context of string theory), then any pair of unbound civilizations will lose their ability to communicate in the future because they will ultimately be separated from each other faster than the speed of light [6–11]. Given this gloomy forecast for communication across cosmological distances if nature is left to its own devices (§2), it is conceivable that mature communities of highly advanced civilizations have already decided to act and move themselves closer together so that they would not be separated forever by the cosmic acceleration. I label this possible unexplored phenomenon *cosmic engineering*. In §3, I examine the prospects for detecting artificial motions or clustering of sources in cosmological data sets. The artificial nature of these signatures would manifest itself as a violation of the standard assumption made in cosmological studies that the observed large scale structure in the Universe was shaped by gravity. Throughout this essay, I use the standard cosmological parameters [2].

II. MAXIMUM AGE OF A DETECTABLE CIVILIZATION

We start by reviewing our ability to detect another civilization which transmits electromagnetic signals towards us and follows the Hubble expansion with no peculiar velocity. Our findings can be easily generalized to any pair of communicating civilizations, with the proper substitution of their spacetime coordinates.

The line-element for a flat universe is given by $ds^2 = c^2dt^2 - a^2(t)(dr^2 + r^2d\Omega)$, where $a(t)$ is the scale factor as a function of cosmic time t and r is the comoving distance. Photon trajectories satisfy $ds = 0$, and so the comoving distance of a civilization that emits radiation at a cosmic time $t_{\rm em}$ and is observed at the current age of the Universe t_0 is given by,

$$r = \int_{t_{\rm em}}^{t_0} \frac{c\ dt}{a(t)} \tag{1}$$

If the civilization continues to emit at a later time $t'_{\rm em}$, then this radiation will be observed by us at a future time t'_0. Since the source maintains its comoving coordinate,

$$r = \int_{t_{\rm em}}^{t_0} \frac{c\ dt}{a(t)} = \int_{t'_{\rm em}}^{t'_0} \frac{c\ dt}{a(t)}, \tag{2}$$

or equivalently

$$\int_{t_0}^{t'_0} \frac{dt}{a(t)} = \int_{t_{\rm em}}^{t'_{\rm em}} \frac{dt}{a(t)}. \tag{3}$$

In terms of the conformal time, $\eta(t) \equiv \int_0^t dt'/a(t')$, equation (3) is equivalent to the condition $(\eta(t'_0) - \eta(t_0)) = (\eta(t'_{\rm em}) - \eta(t_{\rm em}))$. The question of whether this equality can be satisfied for an arbitrary value of the source age, $t'_{\rm em}$, depends on the evolution of the scale factor $a(t)$. It is easy to see that as long as $0 < d\ln a/dt < 1$, this equality can be satisfied for an arbitrary value of $t'_{\rm em}$. This is the case, for example, in a matter-dominated universe where $a \propto t^{2/3}$. However, in a de Sitter universe (which describes our cosmic future) the scale factor grows exponentially and so the integrand on the left-hand-side of equation (3) saturates at a finite value even as $t'_0 \to \infty$. This implies that there is a maximum intrinsic age, $t'_{\rm em}$, over which the source is visible to us. Emission after the source reaches this age will never be observable by us[1] (unless the vacuum energy density which makes up the cosmological

[1]The observed redshift of the source diverges exponentially as $t'_0 \to \infty$ and so does the luminosity

constant decays). The maximum visible age of the distant civilization obviously depends on $t_{\rm em}$ or its currently measured redshift, z_0, which is given by the relation $a(t_{\rm em}) = (1+z_0)^{-1}$.

The evolution of the scale factor is determined by the Friedmann equation,

$$\frac{1}{a}\frac{da}{dt} \equiv H(t) = H_0 \left(\frac{\Omega_M}{a^3} + \Omega_\Lambda\right)^{1/2}, \tag{4}$$

where the density parameters for matter and vacuum add up to unity, $\Omega_M + \Omega_\Lambda = 1$, and $H_0 = 70(h_0/0.7)$ km s^{-1} Mpc^{-1} is the present-day value of the Hubble parameter. Equations (1) and (4) admit analytic solutions [13–16] for $r(t_{\rm em}, t_0)$ in terms of an incomplete elliptic integral, and for the scale factor in the form of

$$a(t) = \left(\frac{\Omega_M}{1-\Omega_M}\right)^{1/3} \left[\sinh\left(\frac{3}{2}\sqrt{1-\Omega_M}H_0 t\right)\right]^{2/3}. \tag{5}$$

Figure 1 shows the emission time, $t'_{\rm em}$, as a function of the future observing time, t'_0. All time scales are normalized by the inverse of the current Hubble expansion rate, $H_0 = (\dot{a}/a)|_{t_0} \approx (14 \text{ Gyr})^{-1}$. As the current source redshift increases, its maximum visible age in the future (i.e. the asymptotic value of $t'_{\rm em}$ for $t'_0 \to \infty$) decreases.

Freely expanding cosmological civilizations will remain visible to us only until they reach some finite age in their rest–frame. The signals emitted beyond that age will never reach us due to the acceleration of the cosmic expansion rate, and so we will never know the whereabouts of these distant civilizations as they get older. Once the observed signal from them freezes at a particular time along their evolution, the luminosity distance and redshift continue to increase exponentially with observation time. The higher the current redshift of a civilization is, the younger it will appear as it fades out of sight.

The upper panel of Figure 2 shows the maximum visible age of a source (starting from the Big Bang) as a function of its currently measured redshift. The lower panel gives the corresponding redshift below which it will not be possible to identify a counterpart to the source in a current deep image of the Universe, even if we continue to monitor this source indefinitely.

Figure 3 shows the future gravitational evolution of the large scale structure in the observed distribution of galaxies around the Milky Way. This N-body simulation forecasts that the Milky Way galaxy is not bound to the nearby Virgo cluster and that all galaxies outside the Local Group (which includes the Milky Way and its nearest massive neighbor, Andromeda) will exit from our Hubble horizon within $\sim 10^{11}$ years.

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distance. Hence, the flux received from the source declines exponentially with increasing observing time t'_0. As the image of the source fades away, it stays frozen at a fixed time along its evolution. This situation is qualitatively analogous to the observed properties of a source falling through the event horizon of a non-spinning black hole [12].

FIGURES

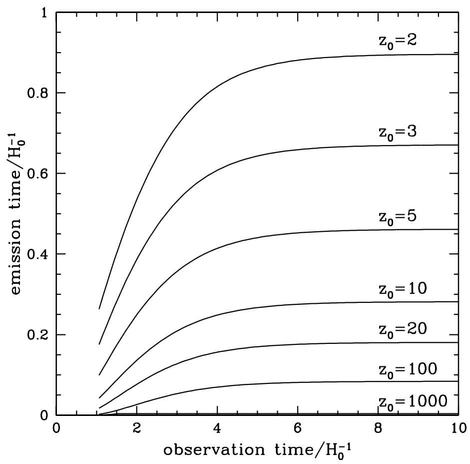

FIG. 1. Emission time of a distant civilization as a function of its future observation time [11]. Time is measured in units of the Hubble time $t_H = H_0^{-1} = 14(h_0/0.7)^{-1}$ Gyr. The current cosmic time since the Big Bang is $t_0 = 0.96H_0^{-1}$. For any currently measured redshift z_0 of a source, there is a maximum intrinsic age up to which we can see that civilization even if we continue to monitor it indefinitely.

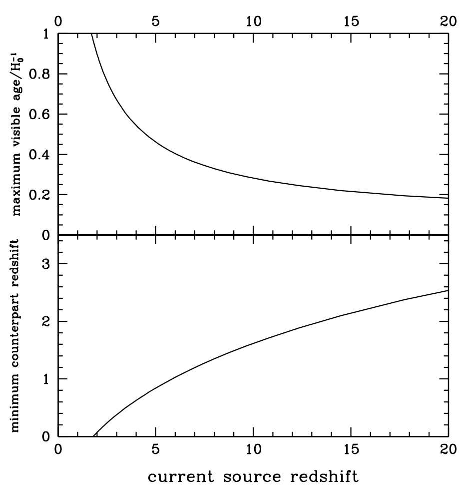

FIG. 2. The upper panel shows the maximum *visible age* of a source [in units of $H_0^{-1} = 14(h_0/0.7)^{-1}$ Gyr] as a function of its currently measured redshift, z_0. The lower panel shows the redshift at which the age of the Universe equals this maximum *visible age* of the source. This is the minimum redshift for which it will be possible, in principle, to identify a counterpart to the source in a current deep image of the Universe. Only the counterparts of all sources at $z_0 < 1.8$ can be traced to the present time [11].

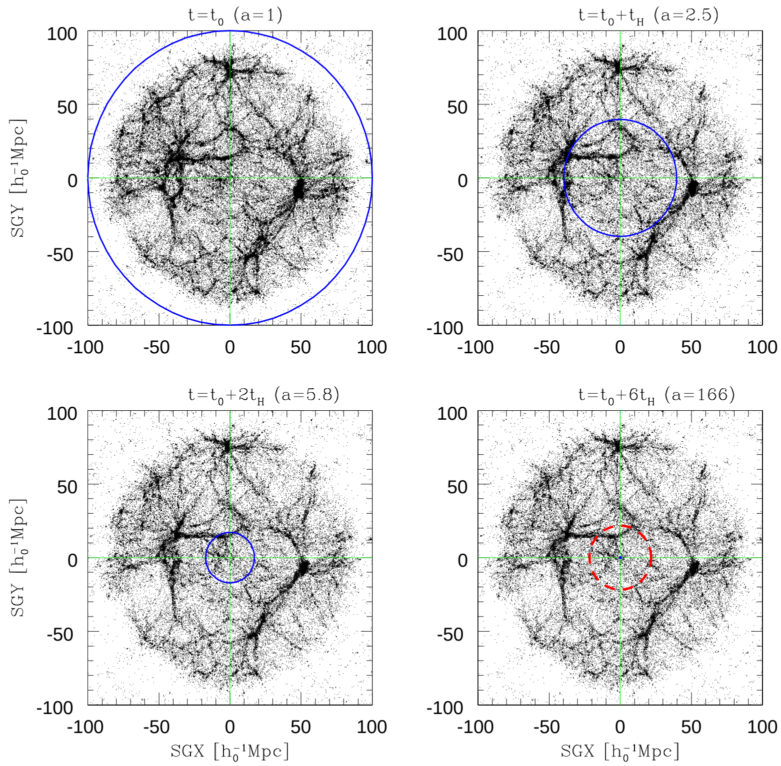

FIG. 3. Future evolution of the distribution of galaxies in the vicinity of the Milky Way [5] in comoving coordinates (with the cosmic expansion taken out). The Milky Way is located at the center of the N-body simulation box. We show galaxies in a slab of thickness $-15 < \mathrm{SGZ} < 15h_0^{-1}$Mpc projected onto the supergalactic XY plane at cosmic times $t = t_0$, $t_0 + t_H$, $t_0 + 2t_H$, and $t_0 + 6t_H$ (corresponding to $a = 1.0$, 2.5, 5.8, and 166) from top left to bottom right. Here t_0 is the present time and $t_H = H_0^{-1} = 14(h_0/0.7)$ Gyr. The thick solid circle in each panel indicates the physical radius of $100h_0^{-1}$Mpc around the Milky Way. In the bottom right panel, the Universe has expanded so much that this circle is no longer visible. Instead, we show the Hubble horizon at a physical radius of $3.6h_0^{-1}$ Gpc as the thick dashed circle. Zooming on our immediate neighborhood, this N–body simulation forecasts that the Milky Way galaxy is not bound to the nearby Virgo cluster and that all galaxies outside the Local Group (which includes the Milky Way and its nearest massive neighbor, Andromeda) will exit from our Hubble horizon within $\sim 10^{11}$ years.

III. ENGINEERED ESCAPE FROM THE COSMIC RIDE

The only way to maintain a community of friendly civilizations across extensive cosmological distances and times is to develop a large peculiar velocity v_p and deviate from the Hubble flow [17]. The least ambitious transportation projects of extragalactic civilizations could be invisible at the relevant distances, unless we happen to eavesdrop on their radio communication signals [18]. Below we calculate the detectable infrared radiation that could result from artificial propulsion of stellar mass objects.

The mean distance between galaxies today is a few Mpc. In order to bridge this gap in less than a Hubble time, the propelled objects need to move at a speed v_p exceeding a few hundred km s^{-1}.

A freely-floating object with a non-relativistic peculiar velocity $v_{\rm p}$ would tend to settle back to the Hubble flow as the Universe expands [2], with $v_{\rm p} \propto a^{-1}$. The minimum power required in order to maintain a fixed value of $v_{\rm p}$ for an object of mass M at a cosmic time t is

$$P_{\rm min} = H(t) M v_{\rm p}^2. \tag{6}$$

This is the minimum power necessary during the coasting phase along the object's trajectory, but the actual needed power $P = P_{\rm min}/\epsilon_{\rm engine}$ would be larger by the inverse of the thermodynamic efficiency of the propulsion engine, $\epsilon_{\rm engine}$. During the initial acceleration period $t_{\rm acc}$ of the object to a speed v_p, the required power $P \sim P_{\rm min}\epsilon_{\rm engine}(Ht_{\rm acc})^{-1}$ could be orders of magnitude larger if $t_{\rm acc} \ll H^{-1}$.

Assuming that a fraction $\epsilon_{\rm IR}$ of $P_{\rm min}$ is emitted as infrared radiation, the observed radiation flux would be

$$f_{\rm IR} = \frac{\epsilon_{\rm IR} H M v_{\rm p}^2}{4\pi d_{\rm L}^2}, \tag{7}$$

where $d_{\rm L}$ is the luminosity distance to the source. For a nearby source ($z \ll 1$) with a flux per unit frequency $f_\nu \sim (f_{\rm IR}/\nu)$ at $\nu \sim 10^{14}$ Hz, we find

$$f_\nu = 0.4 \text{ nJy } \epsilon_{\rm IR} \left(\frac{M}{1M_\odot}\right) \left(\frac{v_{\rm p}}{10^4 \text{ km s}^{-1}}\right)^2 \left(\frac{d_{\rm L}}{10 \text{ Mpc}}\right)^{-2}. \tag{8}$$

The *James Webb Space Telescope* (JWST), scheduled for launch this decade[3], will have a sensitivity of ~ 1 nJy in its deepest and longest infrared exposures. Given that P could be much larger than $P_{\rm min}$, we therefore conclude that JWST might be able to detect the radiation from a single stellar-mass object out to a distance of $\gtrsim 10$ Mpc$(v_p/10^4$ km s$^{-1})$. The flux from different artificially-propelled sources of similar mass at a given distance would scale as the square of their peculiar velocity. The journey time for an object to traverse a distance of ~ 10 Mpc is ~ 1 Gyr$/(v_p/10^4$ km s$^{-1})$. More generally, the comoving distance that each object travels at a constant speed $v_{\rm p}$ is shorter than that traveled by light by a factor of $(v_{\rm p}/c) = 3.33 \times 10^{-2}(v_{\rm p}/10^4$ km s$^{-1})$.

One might wonder whether the propulsion of a stellar-mass object to high speeds is technologically feasible. For the initial acceleration, an advanced civilization could harness natural resources and take advantage of slingshot ejection of stars by binary black hole systems [19] or the tidal disruption of tight stellar binaries by a single supermassive black hole [20]. In fact, hypervelocity stars moving at $\sim 10^3$ km s^{-1} are observed in the halo of the Milky Way galaxy [21,22], and hypervelocity planets are predicted to be ejected with speeds of up to $\sim 10^4$ km s^{-1} [23]. The power requirement for maintaining a constant $v_{\rm p}$ during the

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[2]This can be understood simply from the fact that the de Broglie wavelength of a massive particle, $\hbar/(Mv)$, strectches in proportion to the scale factor a similarly to all length scales in the Universe.

[3]http://www.jwst.nasa.gov/

coasting phase can be satisfied by the nuclear energy reactor carried for the ride, namely the host star. An efficient jet engine that uses the luminosity of a $2M_\odot$ star, 5×10^{34} erg s^{-1}, can provide the necessary power $P_{\rm min}$ to keep the star at a constant peculiar speed of up to $v_p = 2 \times 10^4$ km s^{-1} over a billion years. A star like the Sun can maintain $v_p \approx 10^4$ km s^{-1} over ten billion years.

The deepest fields observed by JWST could set tight limits on the possible existence of such fast-moving sources. The most extreme case of a single stellar-mass object moving near the speed of light would emit radiation that can be detected out to hundreds of Mpc.

IV. DISCUSSION

Given that the cosmic expansion accelerates, intelligent civilizations that were in contact with each other across cosmological distances might have decided to propel themsleves closer together so that they would not be pulled apart and lose contact with each other in the distant future. The related motions or artificial clustering of sources could in principle be identified in cosmological data sets. Cosmic engineering would be an appealing explanation to artificial clustering and dynamics of sources that cannot be naturally produced by gravitational forces on large scales.

We have shown that the power required to move a star at a constant speed across cosmological distances can be supplied the nuclear energy production in the star. Assuming that a significant fraction of this power is emitted in the infrared, the *James Webb Space Telescope* will be able to detect the light from a single stellar-mass object propelled at a constant speed $v_{\rm p}$ out to a distance of $\sim 10(v_{\rm p}/10^4~{\rm km~s^{-1}})$ Mpc. Naturally, the prospects for detectability improve if many such stars would appear to be moving towards the same region of space (which might be protected from the cosmic acceleration by its large overdensity of matter). Spectroscopic detection of multiple sources heading towards the same location with speeds in excess of $\sim 10^4$ km s^{-1} and infrared brightness that scales as the square of their peculiar velocity, would provide an unambiguous signature of non-gravitational propulsion.

If evidence for cosmic engineering is detected, we will be faced with the dilemma whether to join this activity. If we take no action, then within $\sim 10^{11}$ years we will lose communication with all civilizations beyond our Local Group [5]. Cosmological activists may argue that aside from combating loneliness, cosmic engineering would create new jobs and have the added benefit of spurring the economy of our civilization for the next tens of billions of years. If their lobbying effort proves successful, speech writers will have to add updates about the State of the Universe to future State of the Union addresses of American presidents.

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