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Life versus dark energy: How an advanced civilization could resist the accelerating expansion of the universe

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ABSTRACT

The presence of dark energy in our universe is causing space to expand at an accelerating rate. As a result, over the next approximately 100 billion years, all stars residing beyond the Local Group will fall beyond the cosmic horizon and become not only unobservable, but entirely inaccessible, thus limiting how much energy could one day be extracted from them. Here, we consider the likely response of a highly advanced civilization to this situation. In particular, we argue that in order to maximize its access to usable energy, a sufficiently advanced civilization would chose to expand rapidly outward, build Dyson Spheres or similar structures around encountered stars, and use the energy that is harnessed to accelerate those stars away from the approaching horizon and toward the center of the civilization. We find that such efforts will be most effective for stars with masses in the range of $M \sim (0.2\text{–}1)M_{\odot}$, and could lead to the harvesting of stars within a region extending out to several tens of Mpc in radius, potentially increasing the total amount of energy that is available to a future civilization by a factor of several thousand. We also discuss the observable signatures of a civilization elsewhere in the universe that is currently in this state of stellar harvesting.

1. Introduction

While it may be difficult to predict the detailed behavior of an advanced civilization, it is clear that the objectives of any such system would generically require, or at least benefit from, large quantities of usable energy. With this in mind, Freeman Dyson speculated in his 1960 paper [1] that such civilizations would be likely to build structures around stars that are capable of collecting all or most of the light emitted, using this energy and then reemitting the waste heat in the form of high-entropy, infrared or sub-millimeter radiation [2]. Such "Dyson Spheres" are not only a staple of science fiction, but have also been the target of many astrophysical searches and other scientific investigations [3–23].

On timescales of tens of billions of years and longer, the expansion of the universe will ultimately limit the ability of an advanced civilization to accumulate and consume usable energy, a fact that has only been exacerbated by the discovery of dark energy [24,25]. As space expands, stars and other objects fall beyond the cosmic horizon, making it impossible for them to ever again be observed or otherwise interacted with.[1] As dark energy comes to increasingly dominate the total energy density, our universe will enter a phase of exponential expansion, $a(t) \propto e^{Ht}$, where $H = H_0\,\Omega_{\Lambda,0}^{1/2}$ is the asymptotic value of the Hubble constant in terms of the current Hubble constant, $H_0 = 67.8$ km/s/Mpc, and the abundance of dark energy, $\Omega_{\Lambda,0} = 0.692$ [26]. Within approximately 100 billion years, all of the matter that is not gravitationally bound to the galaxies that make up our Local Group will become causally disconnected from the Milky Way, falling beyond the limits of our cosmic horizon [27–30].

In this paper, we speculate about how an advanced civilization would respond to the challenge of living in a universe that is dominated by dark energy. Here we have in mind a civilization that has reached Type III status on the Kardashev scale, which entails the ability to harness the energy produced by stars throughout an entire galaxy [31]. Given the inevitability of the encroaching horizon, any sufficiently advanced civilization that is determined to maximize its ability to utilize energy will expand throughout the universe, attempting to secure as many stars as possible before they become permanently inaccessible. To this end, they could build Dyson Spheres or other such structures around the stars

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[1] Strictly speaking, objects do not cross the horizon, but are increasingly red-shifted as they approach this boundary. In any case, such objects become invisible and unreachable as a result of the expansion of space.

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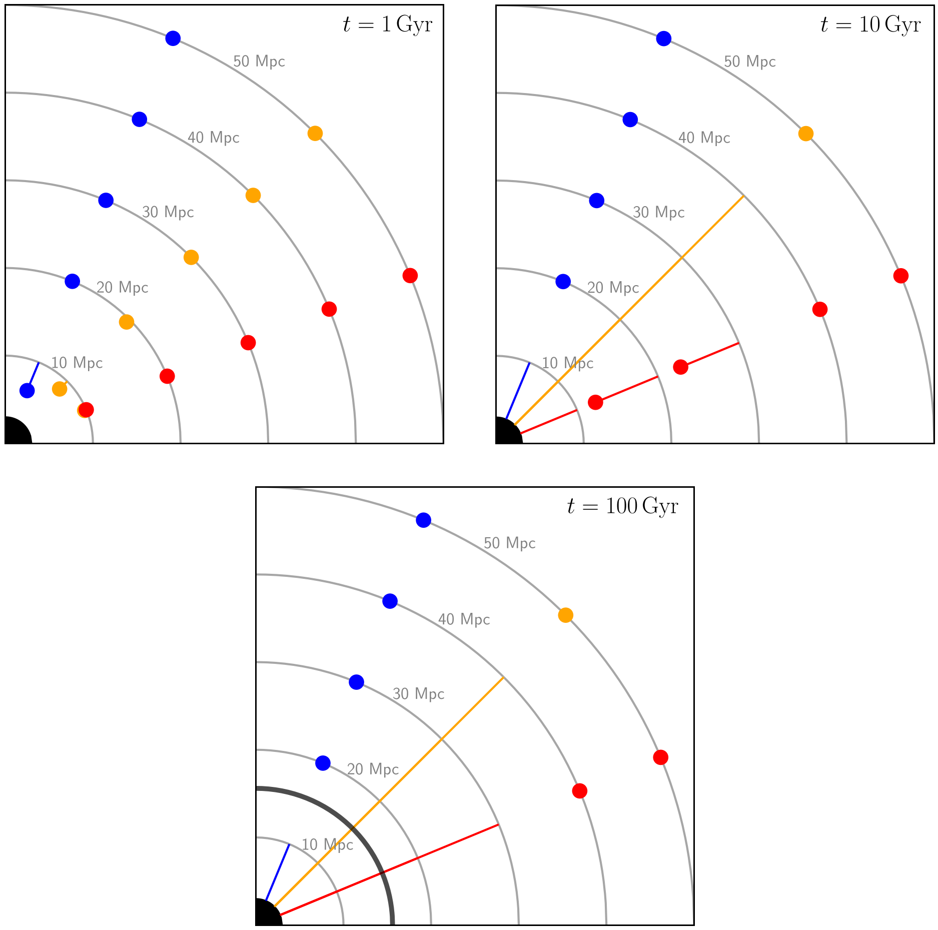

Fig. 1. A cartoon summarizing the prospects for an advanced civilization to transport usable stars to a central location, assuming that such efforts begin in the present epoch ($t = 0$). Blue, yellow and red symbols represent stars with masses of 2, 1 and $0.2 M_{\odot}$, respectively. The colored lines denote the (co-moving) distances those stars have traveled after 1 Gyr, 10 Gyr or 100 Gyr, adopting a maximum speed of 10% of the speed of light and assuming that approximately 100% of the collected energy is converted into kinetic energy of the star ($\eta = 1$). The results shown apply to the case in which each star is encountered as it begins its main sequence evolution. The thick black line in the $t = 100$ Gyr frame represents the horizon at that time in cosmic history. Very distant stars with either very low or high masses will not be collected, as they will either fall beyond the cosmic horizon or evolve beyond the main sequence before reaching their destination. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

that are encountered, and use the energy that is collected to propel those stars toward the center of the civilization, where they will become gravitationally bound and thus protected from the future expansion of space. Broadly speaking, the validity of this conclusion relies only on two modest assumptions, namely that (1) a highly advanced civilization will attempt to maximize its access to usable energy, and that (2) our current understanding of dark energy and its impact on the future expansion history of our universe is approximately correct.

In the following, we will calculate which stars could be effectively harvested in this way. We find that very high-mass stars will often evolve beyond the main sequence before reaching their destination of the central civilization, while very low-mass stars will oftentimes generate too little energy (and thus provide too little acceleration) to avoid falling beyond the horizon. For these reasons, stars with masses in the approximate range of $M \sim (0.2\text{–}1) M_{\odot}$ will be the most attractive targets of such an effort. A civilization that begins to expand in the current epoch, traveling at a maximum speed of 10% (1%) of the speed of light, could harvest stars in this mass range out to a co-moving radius of approximately 50 Mpc (20 Mpc). Unlike more conventional Dyson Spheres, these structures would not necessarily emit in the infrared or sub-millimeter bands, but would instead use the collected energy to propel the captured stars, providing new and potentially distinctive signatures of an advanced civilization in this stage of expansion and stellar collection.

2. Gathering stars from throughout the local universe

The expansion rate of our universe is described by the Friedmann equations. For the case of a spatially flat universe that is dominated by matter and dark energy (with an equation of state of $w = -1$), the first of these equations can be written as follows:

$$\left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G}{3}\left[\frac{\Omega_{M,0}}{a^3} + \Omega_{\Lambda,0}\right], \tag{2.1}$$

where a is the scale factor, $\dot{a}$ is its time derivative, G is the Newtonian gravitational constant, and the current abundances of matter and dark energy are given by $\Omega_{M,0} = 0.308$ and $\Omega_{\Lambda,0} = 0.692$, respectively [26].

Expanding outward at a speed of $v_{\rm exp}$, a civilization could traverse the following co-moving distance as a function of time:

$$d_{\rm CM}(t) = \int_0^t \frac{v_{\rm exp} dt'}{a(t')}. \tag{2.2}$$

When a star is reached, a Dyson Sphere could be constructed and used to accelerate the surrounded star. If a fraction, η, of this energy is somehow[2] transferred into the kinetic energy of the star, its

2 We leave it to the advanced civilization to figure out how exactly this would be accomplished.