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THE HORIZON OF FUTURE INTERGALACTIC TRAVEL

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ABSTRACT

I show that non-relativistic objects traveling in intergalactic space at an initial peculiar velocity v will traverse in the future of the LCDM cosmological model a maximum comoving distance of $\sim (v/1.7H_0)$, irrespective of travel time, where H_0 is the Hubble constant. This follows from the future exponential growth of the scale factor. Hypervelocity stars escaping the halo of the Milky Way galaxy will not go beyond a few tens of comoving Mpc, even over the trillions of years that represent the lifetime of low-mass stars. To reach beyond the Virgo cluster of galaxies, requires an initial peculiar speed $\gtrsim 3 \times 10^3$ km s^{-1}, a hundred times faster than the chemical rockets launched to space so far.

1. INTRODUCTION

The distant future of the standard LCDM cosmological model implies that all galaxies beyond the Milky-Way will eventually exit from our event horizon (Krauss & Starkman 2000; Loeb 2002; Nagamine & Loeb 2003; Busha et al. 2003; Nagamine & Loeb 2004; Heyl 2005; Loeb 2011).

The event horizon is conventionally defined based on the speed of light. The limiting distance shrinks to much smaller scales for non-relativistic motions. Here, we consider the limit imposed by the future exponential expansion of an LCDM cosmology on the maximum comoving distance that can be traversed by non-relativistic astrophysical objects, such as hypervelocity stars or black holes.

The mass budget of the standard LCDM model is currently dominated by a cosmological constant with a density parameter, $\Omega_\Lambda \approx 0.7$ (Planck Collaboration et al. 2020). The future evolution of the scale factor follows the Friedmann-Lemaitre-Robertson-Walker equation for a flat geometry,

$$\left(\frac{\dot{a}}{a}\right)^2 = H_0^2\left[\Omega_\Lambda + \frac{(1-\Omega_\Lambda)}{a^3}\right], \tag{1}$$

where $H_0 \approx 70$ km s^{-1} Mpc^{-1} is the current Hubble constant. The evolution of the scale factor in the distant future, $t \gg t_0$, is to a good approximation, $a \approx \exp\{\sqrt{\Omega_\Lambda}H_0(t-t_0)\}$, where $t_0 = 13.8$ Gyr is the present cosmic time.

2. COMOVING HORIZON FOR NON-RELATIVISTIC MOTION

An object moving through intergalactic space at a non-relativistic peculiar velocity, v, traverses an infinitesimal physical distance adr over a time interval, dt, where r is the radial comoving coordinate. Since the object's momentum declines inversely with the scale factor (equivalent to redshifting its de Broglie wavelength), we get,

$$v = \frac{adr}{dt} = \frac{v_0}{a}, \tag{2}$$

where v_0 is the current value of the peculiar velocity.

The time-integration of equation (2) yields,

$$\Delta r = (r - r_0) = v_0\int_{t_0}^{t}\frac{dt}{a^2} \approx r_{\rm max}\left[1 - e^{-2\sqrt{\Omega_\Lambda}H_0 t}\right], \tag{3}$$

implying that future intergalactic travel in LCDM is limited to traversing a maximum comoving distance, even for an infinite travel time,

$$r_{\rm max} = \frac{v_0}{2\sqrt{\Omega_\Lambda}H_0} = 26\ \text{Mpc} \times \left(\frac{v_0}{3\times10^3\ \text{km s}^{-1}}\right). \tag{4}$$

3. DISCUSSION

Equation (4) sets an upper limit to the distance that galactic winds, driven by present-day supernovae or supermassive black holes (Pillepich et al. 2018), can reach and enrich the intergalactic medium (whose mass can slow them down further).

Hypervelocity stars (Brown 2015), which exit the halo of the Milky Way galaxy at a speed below a few thousand km s^{-1}, will not go beyond a comoving distance of a few tens of Mpc even after trillions of years, the lifetime of low-mass stars (Adams et al. 2005). The gravitational-wave recoil of the black hole remnant from a merger of black hole binaries is also limited to similar speeds (Schnittman & Buonanno 2007; Loeb 2007).

However, the ejection speed could be larger for triple systems involving three black holes (Kulkarni & Loeb 2012) or stars interacting with a black hole binary (Guillochon & Loeb 2015). The traversed distance will be largest for semi-relativistic stars, ejected by binaries of supermassive black holes (Loeb & Guillochon 2016). For $v_0 \sim 0.1c$, these stars can traverse 260 comoving Mpc.

To reach beyond the Virgo cluster of galaxies, requires an initial peculiar speed over $0.01c = 3 \times 10^3$ km s^{-1}, a hundred times faster than the chemical rockets that humanity launched to space so far.

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