On the Importance of Hypervelocity Stars for the Long-Term Future of Cosmology

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In the standard cosmological model, the merger remnant of the Milky Way and Andromeda (Milkomeda) will be the only galaxy remaining within our event horizon once the Universe has aged by another factor of ten, $\sim 10^{11}$ years after the Big Bang. The characteristic wavelength of the cosmic microwave background will be stretched exponentially in time $\propto \exp\{H_{\rm v}t\}$ and exceed the horizon scale $\sim cH_{\rm v}^{-1}$ after $\sim 10^{12}$ years. At that time, the only extragalactic sources of light in the observable cosmic volume will be hypervelocity stars being ejected continuously from Milkomeda. Spectroscopic detection of the evolution in the Doppler shifts of these stars will allow a precise measurement of the vacuum mass density, $\rho_{\rm v} = (3H_{\rm v}^2/8\pi G)$, as well as the mass distribution of Milkomeda. The mean density of Milkomeda's halo will provide a clue for the cosmic matter density $\bar{\rho}_{\rm m}$ when that galaxy was assembled, which is coincidentally comparable to $\rho_{\rm v}$. The sum of the age of the Universe at the time of assembly $\sim H_{\rm v}^{-1}$ and the measured ages of low-mass stars and cooling white dwarfs since then would provide a measure of the time elapsed since the Big Bang.

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Introduction. In the standard LCDM cosmological model [1], the vacuum mass density which just started dominating the cosmic mass budget will remain constant

$$\rho_{\rm v} = 0.7 \times 10^{-29}\ {\rm g\ cm}^{-1}\ , \qquad (1)$$

and so in the future, the scale factor of the Universe will grow exponentially with time $a \propto \exp\{H_{\rm v}t\}$, at a rate

$$H_{\rm v} = \frac{\dot{a}}{a} = \left(\frac{8\pi G\rho_{\rm v}}{3}\right)^{1/2} = (1.6\times 10^{10}\ {\rm yr})^{-1}. \qquad (2)$$

This accelerated expansion has important consequences for observers once the Universe ages by merely 1–2 orders of magnitudes from now. Within $\sim 10^{11}$ yr after the Big Bang, all galaxies outside the Local Group will exit from our event horizon [2, 3]. At that time, the Local Group itself will be a single galaxy, Milkomeda, due to the imminent merger between the Milky Way and Andromeda in only $\sim 5\times10^9$ yr from now [4]. Milkomeda will be dominated by stars of low masses $m_\star \sim 0.1$–$1M_\odot$, for which the lifetime $t_\star \approx 6.3\times10^{12}(m_\star/0.1M_\odot)^{-2.8}$ yr [5] is comparable to the age of the Universe, t. Within ~ 67 e–folds or $\sim 10^{12}$ yr, the wavelength of the cosmic microwave background photons will be stretched by a factor of $\sim 10^{29}$ and exceed the scale of the horizon $R_{\rm hor} \sim cH_{\rm v}^{-1} = 4.9\times10^3$ Mpc. At that time, not only external galaxies but also the nearest extragalactic protons will be pushed out of our horizon and not be available for tracing the cosmic expansion. This realization has led to the naive expectation that an empirical reconstruction of the past cosmic history will become impossible [6–9]. Will future observers be unable to verify the validity of the standard cosmological model?

Here we show that the continuous flow of hypervelocity stars escaping Milkomeda will in fact allow future observers to measure $\rho_{\rm v}$ and the mass distribution within Milkomeda. This information will be sufficient to demonstrate the validity of the standard cosmological model at the above mentioned times.

Cosmology with Hypervelocity Stars. Hypervelocity stars (HVSs) have velocities in excess of the escape velocity of their host galaxy. Such stars were discovered in the Milky Way halo over the past six years [10] and are thought to be produced by stellar interactions with the nuclear black hole SgrA*. Although most of the known HVSs are bright and short-lived due to observational selection effects, one expects that lower mass stars are more commonly ejected from the Galactic center [11]. The ejection rate is low, once per $\sim 10^{5\pm1}$ yr, and is therefore expected to continue into the distant future long before the central reservoir of stars will be depleted in the Milky Way or Milkomeda.

For a spherically-symmetric mass distribution, the orbit of an HVS is purely radial, starting with some ejection velocity $\gtrsim 10^3$ km s^{-1} at $r \sim 0$ and subjected to two radial acceleration terms at $r \ll R_{\rm hor}$,

$$\frac{d^2r}{dt^2} = -\frac{GM(<r)}{r^2} + H_{\rm v}^2 r, \qquad (3)$$

with $M(<r)$ being the galaxy mass interior to a physical radius r. For a total Milkomeda mass of $M_{\rm tot} = 10^{13}M_{13}\ M_\odot$, the second ("cosmological constant") term will start to dominate at radii beyond

$$R_{\rm tran} = \left(\frac{GM_{\rm tot}}{H_{\rm v}^2}\right)^{1/3} = 2.3M_{13}^{1/3}\ {\rm Mpc}. \qquad (4)$$

Figure 1 shows the relative contributions of the two acceleration terms on the right-hand-side of equation (3).

With a typical escaping speed of $\sim 10^3$ km s^{-1}, an HVS will traverse $R_{\rm tran}$ in a time $\sim 2\times10^9$ yr, much shorter than the lifetime of most of the stars ejected from

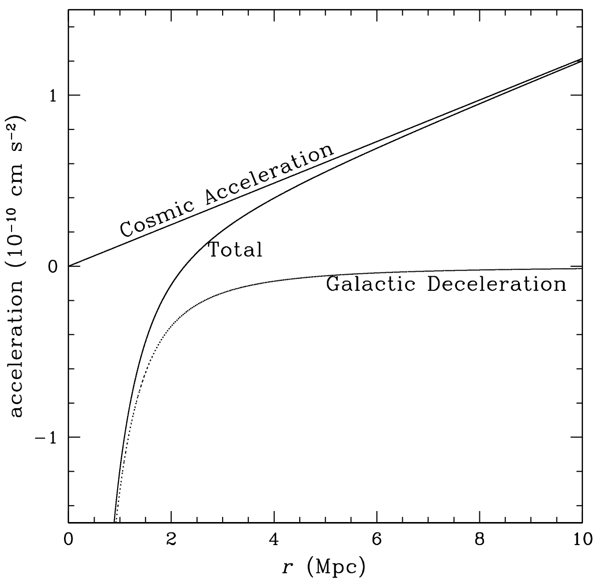

FIG. 1: The net acceleration of an HVS in Milkomeda as a function of radius r (middle line). The Galactic deceleration (lower line) is calculated for a halo with a total mass $M_{\rm tot} = 10^{13} M_\odot$, a virial radius $R_{\rm vir} = 300$ kpc, and a truncated density profile described by Eq. (1) of Ref. [13] (with $R_{200} \equiv R_{\rm vir}$) that fits related numerical simulations. Half of the halo mass lies outside $R_{\rm vir}$. The acceleration due to the cosmological constant (upper line) dominates over the Galactic deceleration at large radii, $r > R_{\rm tran} = 2.3$ Mpc (see Eq. 4).

Milkomeda's center. By using advanced technologies, future observers could measure the acceleration of those stars from the change in the Doppler shift of their spectral lines. The distance of those stars can be found by inferring the intrinsic stellar luminosities from detailed spectroscopic observations. Measurements beyond $R_{\rm tran}$ will determine the value of $\rho_{\rm v}$, whereas closer HVSs will be used to find Milkomeda's mass distribution, $M(<r)$.

Since Milkomeda is surrounded by vacuum, it will have a sharp outer boundary [13]. The boundary is interior to $R_{\rm tran}$ because matter outside $R_{\rm tran}$ is accelerated outwards and cannot be bound gravitationally. The average matter density within the virial radius of Milkomeda $R_{\rm vir} = 300 R_{300}$ kpc can then be measured,

$$\rho_{\rm vir} = 3 \times 10^{-27} \left[\frac{M(<R_{\rm vir})}{5 \times 10^{12}\ M_\odot}\right] R_{300}^{-3}\ {\rm g\ cm^{-3}}. \quad (5)$$

The spherical collapse model implies that a galaxy embedded in a uniform matter-dominated background at early times should virialize with a mean density of $\sim$ 100–200 times the background matter density, $\bar\rho_{\rm m}$ [14]. Future observers will then be able to estimate that the mean background density when Milkomeda had formed was $\bar\rho_{\rm m} \sim (3 \times 10^{-27}\ {\rm g\ cm^{-3}}/200) = 1.5 \times 10^{-29}\ {\rm g\ cm^{-3}}$. This value is coincidentally comparable to the vacuum mass density in equation (1). The age of the Universe when Milkomeda had formed can then be estimated to be $\sim H_{\rm v}^{-1}$, since the total Hubble expansion rate $H = \dot a/a$ satisfies $H^2 = (8\pi G/3)(\bar\rho_{\rm m} + \rho_{\rm v})$. Because the matter density is diluted as $\bar\rho_{\rm m} \propto a^{-3}$, one will then be able to conclude that the Universe must have been dominated by matter at earlier times.

The elapsed time since Milkomeda assembled most of its gas would be measurable from the age envelope of its stars and white dwarfs, $t_\star$. Such a measurement will provide a good estimate for the total time since the Big Bang, $t \approx (H_{\rm v}^{-1} + t_\star)$. The average matter density at t can then be verified to be unmeasurably small, $\bar\rho_{\rm m}(t) \sim \rho_{\rm v} \exp\{-3(H_{\rm v} t - 1)\}$.

At $t \gtrsim 10^{12}$ yr, the HVSs escaping from Milkomeda will be the only extragalactic sources of light filling up the observable volume of the Universe. For stars ejected with an initial speed v_0 from Milkomeda's center at $r = 0$, equation (3) can be integrated to give the velocity $v(r) \equiv (dr/dt)$ as a function of radius at distances $r \ll R_{\rm hor}$. Given a steady ejection rate $\dot N$, the radial profile of the number density of stars $n(r)$ can be derived from the continuity equation,

$$n = \frac{\dot N}{4\pi r^2 v(r)}\ . \quad (6)$$

At $r \sim R_{\rm tran}$ the velocity of an HVS is reduced to $v_{\rm tran} \approx (v_0^2 - v_{\rm esc}^2)^{1/2}$, where $v_{\rm esc}$ is the escape speed from the production site of HVSs in the core of Milkomeda. Beyond $R_{\rm tran}$ the HVS velocity, $v \approx [v_{\rm tran}^2 + H_{\rm v}^2(r^2 - R_{\rm tran}^2)]^{1/2}$, remains nearly constant out to a radius $R_{\rm vel} \equiv (v_{\rm tran}/H_{\rm v}) = 16.3 (v_{\rm tran}/10^3\ {\rm km\ s^{-1}})$ Mpc, at which the cosmic acceleration starts to increase its value significantly. Therefore, at intermediate radii $R_{\rm tran} \lesssim r \ll R_{\rm vel}$ equation (6) yields a power-law density profile, $n \propto r^{-2}$. This profile extends down to $r = 0$ if $v_0 \gg v_{\rm esc}$. In this regime, the total number of HVSs increases linearly with distance. However, at much larger distances $R_{\rm vel} \ll r \ll R_{\rm hor}$ the initial velocity is unimportant, and $v \approx H_{\rm v} r$, allowing one to measure $\rho_{\rm v}$ from the slope of the Hubble diagram ($v \propto r$) rather than from the acceleration in equation (3). In this remote region $n \propto r^{-3}$, and the total number of HVSs grows only logarithmically with distance, providing a limited statistical benefit from improvements in the flux detection threshold of HVSs. Closer to the horizon, the cosmological redshift (which is ignored here for simplicity) makes the total number counts even flatter with decreasing flux. For stellar masses $m_\star \gtrsim 0.5 M_\odot$, the HVS counts saturate at a sub-horizon distance for which the travel time equals the HVS lifetime. For example, solar-mass stars with a lifetime $t_\star = 10^{10}$ yr can only shine while they travel out to a distance of $\sim$ 30 Mpc for an ejection speed $v_0 = 3 \times 10^3\ {\rm km\ s^{-1}}$ and merely $\sim$ 7 Mpc for $v_0 = 10^3\ {\rm km\ s^{-1}}$.

Since the observed energy flux from a star of a given luminosity $L_\star$ is $F_\star = L_\star/(4\pi r^2)$, the total number of HVSs in the sky above an observed flux F is given by

$$N(>F) = 4\pi \int_0^{r_{\max}(F)} nr^2 dr, \quad (7)$$

where $r_{\max}(F) \equiv (L_\star/4\pi F)^{1/2}$. Figure 2 shows the resulting flux distribution, normalized by an HVS ejection rate of $\dot{N} = 10^{-5}\ \mathrm{yr}^{-1}$. For stars with $m_\star \gtrsim 0.5 M_\odot$, this distribution should be trimmed to flatten at the minimum flux corresponding to the distance for which the travel time equals the HVS lifetime. The travel time to a radius r can be read directly from Figure 2, since it equals $(N/\dot{N}) = 10^5 N$ yr in a steady state. Stars with $m_\star = 0.5 M_\odot$ and $L_\star = 0.07 L_\odot$ (assumed to be forming steadily out of the gas reservoir in Milkomeda's nucleus) are the most luminous HVSs which could in principle be observed out to the horizon distance $R_{\rm hor}$, since their lifetime $t_\star \sim 7\times 10^{10}$ yr is comparable to the travel time from Milkomeda to $\sim R_{\rm hor}$. A civilization living around an M-dwarf HVS with $m_\star \lesssim 0.5 M_\odot$ will have the privilege of taking a *habitable* one-way trip beyond the horizon of Milkomeda.

Conclusions. In the distant future, runaway HVSs from Milkomeda will be the only extragalactic sources of light filling up the observable volume of the Universe. We have shown that a spectroscopic detection of the evolution in their Doppler shifts could be used by future observers to validate the standard cosmological model even at a time when the wavelength of the relic radiation from the hot Big Bang exceeds the scale of the horizon.

Indirect clues might also be available. The existence of an early radiation-dominated epoch could be inferred by measuring the abundance of light elements in metal-poor stars and interpreting it with a theory of Big Bang nucleosynthesis. The mass fraction of baryons within Milkomeda could be assumed to be representative of the mean cosmic value at early times. The nucleosynthesis theory can then be used to find the necessary radiation temperature $T_\gamma \propto a^{-1}$, such that the correct light element abundances would be produced. This would lead to an estimate of the time when matter and radiation had the same energy densities. Since density perturbations grew mainly after that time, it will be possible to estimate the amplitude of the initial density fluctuation on the mass scale of $M_{\rm tot}$ that was required for making Milkomeda at a time $(t - t_\star) \sim H_{\rm v}^{-1}$ after the Big Bang. Without a radiation-dominated epoch, this amplitude could have been arbitrarily low at arbitrarily early times. Future astronomers may already have cosmology texts available to them, but even if they do not, we have outlined a methodology by which they will be able to arrive at, and empirically verify, the standard cosmological model.

One might wonder whether the signal shown in Figure 1 can be used today to measure $\rho_{\rm v}$ outside the Local Group. Conceptually, such a measurement would be contaminated by the large matter inhomogeneities that exist at distances smaller than tens of Mpc around the Virgo cluster. But even if one were interested in mapping the mass distribution of those inhomogeneities [16], the instrumental requirements are extremely challenging. With state-of-the-art spectrographs using a laser frequency comb [17] installed in the next generation of large telescopes [18], one might hope to achieve at best a velocity precision of ~ 1 cm s^{-1}, which corresponds to an acceleration sensitivity of $\sim 3\times 10^{-9}$ cm s^{-2} over a period of a decade. Unfortunately, this sensitivity threshold is still much larger than the expected acceleration amplitude of $\sim 10^{-10}$ cm s^{-2} at the largest possible distance of ~ 14 Mpc, which an HVS with a velocity of $\sim 10^3$ km s^{-1} could reach during the current age of the Universe. Although one could attempt to measure the velocity drift over a longer period of time, the actual acceleration sensitivity will be much worse than the best-case value stated above given the faintness of a single star at that distance. Future generations of experimentalists will have $\sim 10^{12}$ yr to improve upon this instrumental

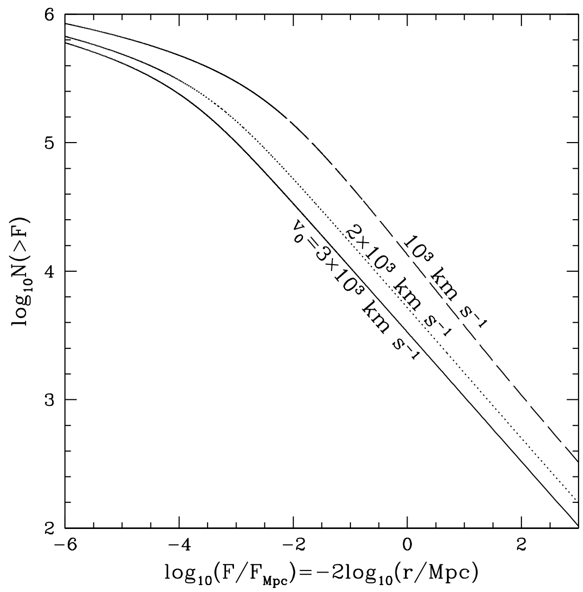

FIG. 2: Number of HVSs out to a distance r (in Mpc) or with an observed flux $> F$ (in unit of $F_{\rm Mpc} \equiv L_\star/(4\pi \times {\rm Mpc}^2)$. Results are shown for an HVS ejection rate $\dot{N} = 10^{-5}\ \mathrm{yr}^{-1}$ and the same mass distribution of Milkomeda that was used in Fig. 1. For long-lived stars with $L_\star = 0.07 L_\odot$ ($m_\star = 0.5 M_\odot$ and $t_\star = 7\times 10^{10}$ yr), the flux unit $F_{\rm Mpc} = 2.34 \times 10^{-18}$ erg cm^{-2} s^{-1} corresponds to a specific flux of ~ 0.8 nJy or an AB magnitude of 31.7 at a wavelength of $\sim 1\mu$m and is comparable to the expected 1-σ sensitivity of the *James Webb Space Telescope (JWST)* [15]. The different lines correspond to different ejection speeds at $r = 0$, namely $v_0 = 10^3$ km s^{-1} (upper line), 2×10^3 km s^{-1} (middle line), and 3×10^3 km s^{-1} (lower line).

performance before it becomes crucial for validating the standard cosmological model.

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[1] E. Komatsu, et al., Astrophys. J. Supp. **192**, 18 (2011).
[2] A. Loeb, Phys. Rev. **D65**, 047301 (2002). See also chapter 8 in A. Loeb, "How Did the First Stars and Galaxies Form?", Princeton Univ. Press (2010).
[3] K. Nagamine, & A. Loeb, New Astronomy **8**, 439 (2003); *ibid* **9**, 573 (2004); Y. Hoffman, et al., JCAP **10**, 16 (2007); P. Araya-Melo, et al., Mon. Not. R. Astron. Soc. **399**, 97 (2009).
[4] T. J. Cox, & A. Loeb, Mon. Not. R. Astron. Soc. **386**, 461 (2008).
[5] F. C. Adams, P. Bodenheimer, & G. Laughlin, Astron. Nach. **326**, 913 (2005).
[6] T. Rothman, & G. F. R. Ellis, The Observatory **107**, 24 (1987).
[7] L. M. Krauss, & R. J. Scherrer, General Relativity and Gravitation **39**, 1545 (2007); see also L. M. Krauss, & G. D. Starkman, Astrophys. J. **531**, 22 (2000).
[8] F. C. Adams, & G. Laughlin, Rev. Mod. Phys. **69**, 337 (1997).
[9] A. A. Starobinsky, Grav. Cosm. **6**, 157 (2000); T. Chiueh, & X.-G. He, Phys. Rev.**D65**, 123518 (2002); E. H. Gudmundsson, & G. Björnsson, Astrophys. J. **565**, 1 (2002).
[10] W. Brown, preprint arXiv:0811.0571 (2008), and references therein. See also updated review in http://www.cfa.harvard.edu/events/2010/dyn/videos/Brown.mov
[11] J. A. Kollmeier, & A. Gould, Astrophys. J. **664**, 343 (2007).
[12] J. F. Navarro, C. S. Frenk, & S. D. M. White, Astrophys. J. **490**, 493 (1997).
[13] M. T. Busha, et al., Mon. Not R. Astron. Soc. **363**, L11 (2005); see also Astrophys. J. **596**, 713 (2003) and Astrophys. J. **665**, 1 (2007).
[14] J. E. Gunn, & J. R. Gott, Astrophys. J. **176**, 1 (1972).
[15] http://www.jwst.nasa.gov/
[16] O. Y. Gnedin, et al., Astrophys. J. **634**, 344 (2005); B. D. Sherwin, A. Loeb, & R. M. O'Leary, Mon. Not. R. Astron. Soc. **386**, 1179 (2008).
[17] S. Lopez, Science **321**, 1301 (2008).
[18] http://www.eso.org/sci/facilities/eelt/; http://www.gmto.org/; http://www.tmt.org/