Ultra Long-Term Cosmology and Astrophysics

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We examine astronomical observations that would be achievable over a future timeline corresponding to the documented history of human civilization so far, $\sim 10^4$ years. We examine implications for measurements of the redshift drift, evolution of the CMB, and cosmic parallax. A number of events that are rare on the scale of centuries will become easily observable on a timescale $\sim 10^4$ years. Implications for several measurements related to gravity are discussed.

I. INTRODUCTION

While most astronomical observations correspond to a "snapshot" of some object at a fixed time, there has been increasing interest in longer-term observations. Perhaps the best current example is the Vera C. Rubin Observatory, which will conduct a 10-year survey of the entire sky. However, our ability to utilize data extending over long (past) timelines is hampered by the relatively short history of astronomy itself. The era of optical telescopes comprises the past 500 years, with significant improvements over the past century. Other branches of astronomy are much more recent, with radio astronomy nearing its first century of operation, and observations in other frequencies dating back only to the dawn of the Space Age and the ability to send telescopes above the Earth’s atmosphere (a timescale which lies well within both authors’ lifetimes). Very long term observations have been limited to easily measured quantities (e.g., the orbits of the planets).

Now that we are well-situated within the era of modern astronomy, we pose the following question: what kinds of observations would be achievable with an extremely long future timeline? We need to make an important distinction at this point. Obviously, we can anticipate technological progress to result in improved instrumentation in the future, allowing for entirely new windows for observing the universe (as an example, one need look no further than the recent birth of gravitational wave astronomy). However, such progress is nearly impossible to predict, rendering intelligent discussion about future technology extremely difficult. Instead, we are interested in observations that are made possible only by a sufficiently long timeline. For example, a direct measurement of the rate of visible supernovae within the Galaxy requires that we observe over a sufficiently long time to obtain a statistically significant number of events; in this case it is the long timeline, and not some supposed future technology, that allows the measurement to be made. In what follows, we will assume a current level of technology extrapolated into the future. Thus, our claims will represent a lower bound on what could be achieved with ultra long-term observations.

What is a reasonable timescale over which future observations are plausible? The recorded history of human civilization is nearly 10,000 years old, so we will assume that we may extrapolate forward by a similar order of magnitude. A timescale of 1000 years is too short; we already have astronomical data going back this far. Similarly, 100,000 years seems excessively optimistic for the future lifespan of our civilization given that it exceeds recorded history and new technologies often bring existential risks. So we will base our discussion on an observational timeline from today to 10,000 years in the future.

II. COSMOLOGY

The universe is roughly 13.8 Gyr old [1], which sets the typical timescale over which significant changes can be observed in the overall expansion. Then the typical fractional change in any quantity related to the expansion observed on a time interval $\Delta t$ will be $\sim \Delta t/(13.8 \text{ Gyr})$.

The earliest proposal to use long-timescale observations in cosmology is the Sandage-Loeb test [2,3]. The Sandage-Loeb test is based on the idea of redshift drift, the change in the redshift $z$ over some time interval $\Delta t$ due to the expansion of the universe. Suppose we are measuring the redshift $z$ of an object at some initial time, and we remeasure

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this redshift at a later time interval $\Delta t$. Then the change in redshift observed over this interval is

$$\Delta z = H_0 \Delta t \left( 1 + z - \frac{H(z)}{H_0} \right), \quad (1)$$

where $H_0$ is the locally-measured value of the Hubble parameter, and $H(z)$ is its value at the redshift $z$. For $z$ of order unity, $\Delta z$ is on the order of $\Delta t$ divided by the age of the universe. A proposed 10-year observation timeline yields $\Delta z \sim 10^{-9}$, which is challenging to detect even with the next generation of large ground-based telescopes or HI 21-cm observatories. However, with our assumed timeline of $\Delta t = 10^4$ yr, we obtain $\Delta z \sim 10^{-6}$, an achievable sensitivity with existing spectrographs.

The expansion of the universe also causes the cosmic microwave background (CMB) to evolve in time. The future evolution of the CMB was first discussed by Lange and Page and Zibin, et al., and the possibility of measuring the evolution was discussed in detail in Refs. Consider first the monopole (i.e., the CMB temperature). This temperature, $T$, scales as the inverse of the scale factor $a$, so the time derivative of the temperature is

$$\dot{T} = -HT. \quad (2)$$

Evaluated at the present, we obtain $\dot{T} = 2 \times 10^{-10}$ K/yr. Abitbol et al. examined the plausibility of measuring this change in $T$ with a ten-year mission and argued that it seems impractical with current technology, largely because of foreground interference. While a $10^4$ yr timeline produces a relatively large $\Delta T$ ($\sim 10^{-6}$ K), it also opens up the possibility of nontrivial variation in the foregrounds due to evolution of the Galaxy.

Moss et al. argue that time variation of the higher order multipoles would require $\Delta t \approx 4000$ yr, well within the timeline proposed here, while the change in the dipole would be detectable over a much shorter timescale. Note that the former is due to the cosmological evolution of the CMB itself, while the latter arises from the peculiar velocity of the solar system motion relative to the zero-dipole frame of the CMB. However, Loeb pointed out that the time variation of the quadrupole also receives a contribution from the motion of the solar system. This change in the quadrupole moment $Q$ is at the level of

$$\frac{\dot{Q}}{Q} \approx 10^{-9} \text{yr}^{-1}, \quad (3)$$

an order of magnitude larger than expected from the intrinsic evolution of the CMB. Again, this would be easily detectable on the $10^4$ yr time frame considered here. (See also Ref. for a review of some of the topics in this section and the following one.)

### III. COSMIC PARALLAX

Annual parallax, caused by the Earth’s orbit about the Sun, provided the earliest method to directly measure the distances to the nearest stars. In addition to this motion, the solar system is moving with respect to the CMB frame at $369 \pm 0.9$ km s$^{-1}$. (As noted in the previous section, this motion will eventually result in detectable variations in the CMB). Over a sufficiently long timescale, this “secular” parallax will allow the measurement of distances to quite distant objects. This possibility was first suggested by Kardashev, and has been examined more recently by several others. This parallax shift is given by

$$|\pi| = 77.8 r^{-1} |\sin \beta| \mu\text{arcsec yr}^{-1} \text{Mpc}. \quad (4)$$

where $r$ is the distance to the object and $\beta$ is the angle between the direction to the object and the direction of motion of the solar system. The application of secular parallax to nearby galaxies could provide a measurement of the Hubble parameter $H_0$, while quasar parallaxes would constrain the dark energy equation of state. All of these discussions assume an observational timeline of 1-10 years.

Now consider what is possible with an observation time of $10^4$ years. In that case, with $\sin \beta \sim 1$, we get a parallax angle of

$$\theta \sim 0.8 r^{-1} \text{arcsec Mpc}. \quad (5)$$

A galaxy like Andromeda (M31) at a distance of 0.75 Mpc would show a parallax on the order of the annual parallax of Proxima Centauri. The distances to low-redshift galaxies would be easily measurable on this timescale and could establish a robust calibration of the cosmological distance ladder. However, a major error is introduced by the peculiar velocities of the galaxies themselves, which cannot simply be removed with a large sample because of
coherent galaxy flows. Ironically, this source of error also scales up with observation time. Techniques to correct for these peculiar velocities using a large sample of galaxies are discussed in Refs. [14–17]. In the case of quasars, the sparse sampling reduces the effects of coherence, and it has been argued that the proper motion errors will decrease significantly as a function of time [13].

This leads naturally to the possible measurement of transverse velocities using a very long time baseline [19], which can be used to confirm the isotropy of the cosmic expansion beyond transverse speeds induced by large-scale structure and could potentially measure the real-time evolution of the baryon acoustic oscillations that serve as a standard ruler in cosmology [20]. At a redshift of $z \sim 0.5$, the proper motion expected from cosmic expansion for the first acoustic peak is $\sim 0.012$ arcseconds per $10^4$ years, which should be measurable on the corresponding angular scale of 4.5°. Even for static objects, the apparent fractional compression is 15 $\mu$as per year in the local universe, implying a measurable change of 0.15 arcseconds over $10^4$ years.

### IV. RARE EVENTS

Events that are rare on the scale of centuries can be measured with statistical significance on the scale of $10^4$ years, while events so rare that they have not yet been observed might become observationally accessible on this timescale. Among the former are supernovae in our galaxy, for which we currently have a poor estimate of the rate. The number of visible supernovae within the past 1000 years is half a dozen, but most supernovae in our galaxy would have been obscured. However, we can now observe the neutrinos from any core collapse supernova in the Galaxy directly. This rate has been estimated at $1 \pm 2$ supernovae per century. So over the next 10,000 years, we would expect to observe 100–200 core collapse supernovae, allowing for an estimate of the total rate with an error of about 10%.

The next 10,000 years are likely to see several potentially destructive astronomical events. Over this time period, we would expect to observe ~1 meteorite impact with a 100 m diameter, corresponding to an impact energy of 100 megatons of TNT, along with ~10 Tunguska sized objects [21]. Solar flares with energy on the order of $10^{34}$ erg have been predicted to occur on the order of once every 2000 years [22], so we would expect to observe ~5 such events over the next 10,000 years. Note that these events would have an energy roughly 100 times as large as the Carrington Event [23]. (See Ref. [24] for a more detailed discussion.) For both meteorite impacts and solar flares, the probability of an extinction-level event over the next 10,000 years is extremely small.

Over $10^4$ years, it should also be possible to observe a massive Wolf-Rayet star, like Apep (2XMM J160050.7–51424), collapse to a black hole, and produce a gamma-ray burst (most likely not in our direction) within our own galaxy [25]. Finally, within the next 10,000 years, it will be possible to observe three transits of Mercury that coincide with a total solar eclipse, the soonest in the year 9966, while a transit of Venus simultaneous with a total solar eclipse will take place just outside of our fiducial time frame (year 15,232) [26].

### V. GRAVITY

The best current bounds on the time variation of Newton’s constant come from ranging measurements to Mars and the Moon [27]. The Mars data give $G/G = 0.1 \pm 1.6 \times 10^{-13}$ yr$^{-1}$ [28], while the limit from the Moon is $G/G = 4 \pm 9 \times 10^{-13}$ yr$^{-1}$ [29]. While one might expect these limits to scale up with observation time, this is not the case for the Mars limit. The reason is that the orbit of Mars does not constrain $G$ directly; instead it puts an upper bound on the change in $GM_\odot$. The current limit is close to the estimates of solar mass loss from light and the solar wind [28]. Thus, any ultra long-term observations of the Mars ephemeris will not constrain the change in $G$ but will instead provide precision estimates of solar mass loss. The Moon, of course, is moving further away from the Earth as it steals our angular momentum, but this effect can be disentangled from the effect of changing $G$ [30]. The accuracy of these limits scales as the square of the time span [29], which currently corresponds to several decades. Increasing this by a factor of ~1000 will significantly improve the bound on $G/G$.

Constraints on the stochastic gravitational wave background at low frequencies can be steadily improved over time with Pulsar Timing arrays [31], as well as using extragalactic proper motion [20]. The signal-to-noise for gravitational waves at a fixed frequency will scale as $t^{1/2}$ [32], although this does not take into account further improvements from adding additional pulsars to the array.

A 10,000 year time span will also allow better constraints on the proper motion of SgrA* [33] and its closest stars [34], improving current limits on a possible binary companion, invisible stars and stellar remnants, and dark matter near the Galactic center.
VI. DISCUSSION

Astronomy and cosmology with an ultra-long timescale will allow a multitude of observations and measurements that are intrinsically limited by our current relatively short timescale for modern astronomy. We do not pretend that the discussion presented here is exhaustive; we suspect that there are potentially many other observations that such a long timescale would enable. A related question, not addressed here, is the issue of maintaining scientific records over a 10,000 year period. Such problems have been examined in connection with nuclear waste storage [35] and related issues [36]. We also do not consider the possibility of civilizations collapse, in which case our descendants will have more important matters to attend to than astronomy.

Acknowledgments

We thank S. Taylor and G. Benford for helpful discussions. A.L. was supported in part by the Black Hole Initiative, which is funded by a grant from JTF and GBMF. R.J.S. was supported in part by the Department of Energy (DE-SC0019207). The authors have no competing interests to declare that are relevant to the content of this article. Data sharing is not applicable as no datasets were generated or analyzed during the current study.

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