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DIRECT MEASUREMENT OF COSMOLOGICAL PARAMETERS FROM THE COSMIC DECELERATION OF EXTRAGALACTIC OBJECTS

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ABSTRACT

The redshift of all cosmological sources drifts by a systematic velocity of order a few meters per second over a century as a result of the deceleration of the universe. The specific functional dependence of the predicted velocity shift on the source redshift can be used to verify its cosmic origin and to measure directly the values of cosmological parameters, such as the density parameters of matter and vacuum, Ω_M and Ω_Λ , and the Hubble constant H_0 . For example, an existing spectroscopic technique, which was recently employed in planet searches, is capable of uncovering velocity shifts of this magnitude. The cosmic deceleration signal might be marginally detectable through two observations of $\sim 10^2$ quasars set a decade apart, with the HIRES instrument on the Keck 10 m telescope. The signal would appear as a global redshift change in the Ly α forest templates imprinted on the quasar spectra by the intergalactic medium. The deceleration amplitude should be isotropic across the sky. Contamination of the cosmic signal by peculiar accelerations or local effects is likely to be negligible.

Subject heading: cosmology: theory

1. INTRODUCTION

Most conventional methods for measuring the values of cosmological parameters rely on the determination of the luminosity distance to extragalactic sources with known redshifts. Consequently, these methods must make a priori assumptions about the intrinsic luminosity of the sources and are often plagued by evolutionary effects or systematic uncertainties (such problems are particularly acute for galaxies [Tinsley 1977] but less so for Type Ia supernovae [Garnavich et al. 1997; Perlmutter et al. 1998].) The alternative approach of using the spectrum of microwave background anisotropies for the same purpose (Jungman et al. 1996; Zaldarriaga, Spergel, & Seljak 1997; Bond, Efstathiou, & Tegmark 1997 and references therein) suffers from partial degeneracies between different cosmological parameters and might be compromised by foreground source contamination. In this Letter, I show that a direct measurement of the deceleration of the universe is not far out of reach of current technology and might be used to determine the values of the cosmological parameters in the future.

The search for a small reflex motion of stars caused by potential planetary companions has recently led to the development of an advanced spectroscopic technique that yields radial velocity errors of $\sim 3 \text{ m s}^{-1}$ (Butler et al. 1996 and references therein). The technique utilizes a fast echelle spectrograph and an iodine absorption cell placed at the spectrometer entrance slit. The superimposed iodine lines provide a reference wavelength frame against which the radial velocity shifts of the stars are measured. The technique currently reaches a sensitivity of $\sim 3 \text{ m s}^{-1}$ for a 10 minute exposure on a $B \sim 6$ mag star using a 3 m telescope and is primarily limited by photon statistics. Extrapolation of this sensitivity to 100 hr of integration on the Keck 10 m telescope should allow for the detection of a similar velocity shift in the spectrum of a $B \sim 16$ mag source. In § 2, I will show that a velocity shift of a few meters per second is expected to occur over a century in the spectrum of extragalactic objects at high redshifts, merely because of the deceleration of the universe. Measurement of this shift for a sufficiently large statistical sample of extragalactic objects could then be used to determine the values of

the fundamental parameters that define the geometry of the universe. As an illustrative example, I will consider in § 3 the expected redshift drift of the Ly α forest in quasar spectra. Contamination of the cosmic deceleration signal by local peculiar accelerations will be shown to be negligible.

2. THE COSMIC SIGNAL

We would like to evaluate the expected variation of the cosmic redshift of a particular extragalactic source with time. For simplicity, let us assume at first that the source does not possess any peculiar velocity or peculiar acceleration, so that it maintains a fixed comoving coordinate ($dr_s = 0$). The radiation emitted by the source at two different times t_s and $t_s + \Delta t_s$ will be observed at later times t_0 and $t_0 + \Delta t_0$, related by (Weinberg 1972, p. 416)

$$\int_{t_s}^{t_0} \frac{dt}{a(t)} = \int_{t_s + \Delta t_s}^{t_0 + \Delta t_0} \frac{dt}{a(t)}, \quad (1)$$

where $a(t) = (1 + z)^{-1}$ is the scale factor of the universe, normalized to unity at zero redshift when the age of the universe is t_0 . For $(\Delta t/t) \ll 1$, equation (1) yields the standard redshift factor between the observation and emission time intervals $\Delta t_s = [a(t_s)/a(t_0)]\Delta t_0$. The source redshift changes during this time interval by the amount

$$\begin{aligned} \Delta z &\equiv \frac{a(t_0 + \Delta t_0)}{a(t_s + \Delta t_s)} - \frac{a(t_0)}{a(t_s)} \approx \left[\frac{\dot{a}(t_0) - \dot{a}(t_s)}{a(t_s)} \right] \Delta t_0 \\ &= \left[\frac{\dot{z}_s}{(1 + z_s)} - (1 + z_s)\dot{z}_0 \right] \Delta t_0, \end{aligned} \quad (2)$$

where an overdot indicates a time derivative, and the second equality was derived by Taylor-expanding the scale factor to leading order, $a(t + \Delta t) \approx a(t) + \dot{a}(t)\Delta t$. Note that the redshift change, $\Delta z \propto [\dot{a}(t_0) - \dot{a}(t_s)]$, results from the evolution of $\dot{a}$ with cosmic time, namely, from the deceleration of the universe. The Friedmann equations can be used to relate $\dot{z} = -(1 + z)^2\dot{a}$ to the matter content of the universe, yielding

$\dot{z} = -H_0(1+z)[\Omega_M(1+z)^3 + \Omega_R(1+z)^2 + \Omega_\Lambda]^{1/2}$, where $H_0 \equiv \dot{a}(t_0)/a(t_0)$ is the Hubble constant, Ω_M and Ω_Λ are the cosmological density parameters of matter and vacuum (the cosmological constant), respectively, and $\Omega_R \equiv (1 - \Omega_M - \Omega_\Lambda)$. In summary, we get a spectroscopic velocity shift

$$\Delta v \equiv \frac{c\Delta z}{(1+z_s)} = -\{[\Omega_M(1+z_s) + \Omega_R + \Omega_\Lambda(1+z_s)^{-2}]^{1/2} - 1\} H_0 \Delta t_0 c, \quad (3)$$

where c is the speed of light. This shift vanishes for an empty universe ($\Omega_M = 0$, $\Omega_\Lambda = 0$) and turns positive for an inflating Ω_Λ -dominated universe. For $\Omega_\Lambda = 0$, we obtain $\Delta v = -2 \text{ m s}^{-1} h_{65} [(1 + \Omega_M z_s)^{1/2} - 1] (\Delta t_0 / 10^2 \text{ yr})$, where $h_{65} = (H_0 / 65 \text{ km s}^{-1} \text{ Mpc}^{-1})$. Note that the low-redshift expansion of equation (3) yields $\Delta v = -q_0 H_0 \Delta t_0 c z$ as expected, where $q_0 = -(\ddot{a}/\dot{a}^2)|_{t_0}$ is the deceleration parameter at t_0 . Examples of extragalactic sources for which a detection of the cosmic signal might be feasible will be discussed in § 3.

Finally, we consider contaminating effects. Any change in the comoving coordinate of the source caused by a peculiar velocity, δv , would only modify the redshift change in equation (3) by a correction of order $\sim(\delta v/c) \ll 1$ (assuming $z_s \gtrsim 1$). This correction is only a fraction of a percent, given the characteristic amplitude of peculiar flows in the universe. The effect of peculiar accelerations could be more significant. First, we note that the peculiar acceleration of the Sun relative to the Galaxy is comparable to the cosmic signal but can be easily separated from it based on its known direction and magnitude (as the cosmic deceleration must be isotropic). In comparison with the cosmic deceleration signal of $\sim H_0 c$ in equation (3), the typical acceleration inside a virialized object of a density δ , in units of the critical density, and a velocity dispersion σ is only a fraction $\sim(\sigma/c)\delta^{1/2}$ of the cosmic signal. Given the characteristic values of $(\sigma/c) \sim 10^{-3}$ to 10^{-2} in galaxies or galaxy clusters, it is clear that the peculiar acceleration can compete with the cosmic deceleration signal only when $\delta \gtrsim 10^4$, i.e., in the very dense cores of virialized objects. Most of the mass in the universe resides in the outer envelopes of such objects, where the peculiar accelerations are much smaller than the cosmic deceleration signal. Moreover, as the peculiar accelerations are induced by local effects and hence have a random sign, their significance could be further diminished by averaging over a sufficiently large statistical sample of extragalactic objects.

3. ILLUSTRATIVE EXAMPLES

There are probably several innovative ways to measure the velocity drift predicted by equation (3). Below I consider two straightforward examples to illustrate the feasibility of such a measurement.

Luminous quasars are the brightest extragalactic sources, but the large width of their broad emission lines ($\gtrsim 10^3 \text{ km s}^{-1}$) and their substantial intrinsic variability renders the use of their spectral lines for the detection of the cosmic deceleration signal impractical. However, the rich absorption-line forest imprinted on the continuum flux of quasars by the intergalactic medium provides an ideal template for this purpose. The width of the Ly α absorption lines is only $\sim 20 \text{ km s}^{-1}$, and the metal lines are even narrower. There are hundreds of detectable Ly α lines per unit redshift down to H I column densities $\sim 10^{13} \text{ cm}^{-2}$ (D.

Tytler 1998, private communication). The existence of absorption lines across the entire range of redshifts out to the quasar allows one to separate the cosmic deceleration signal from contaminating effects, based on the particular functional dependence on redshift predicted by equation (3). Moreover, the cosmic signal should be isotropic across the sky in difference from any local effect. In total, there are $\sim 10^2$ quasars with $B \sim 16$ mag over the sky, for which the Ly α forest can be observed from the ground, i.e., with $z_s \gtrsim 2.5$ (Hartwick & Schade 1990). The cosmic signal can then be searched for through a cross-correlation analysis of the Ly α forest template in the spectrum of these quasars, taken at two different times with the HIRES instrument on the Keck 10 m telescope. Because the velocity drift is a function of redshift, the cross-correlation analysis should be done by using the functional form predicted by equation (3) as a kernel, and by exploring different possible values of the cosmological parameters. To illustrate the feasibility of this project, we first consider a time separation of a century, namely, $\Delta t_0 = 100 \text{ yr}$. Each pixel in the Keck HIRES spectrum is 2 km s^{-1} wide. According to equation (3) the cosmic velocity shift would be $\sim 10^{-3}$ of a pixel width. Assuming that the Ly α forest flux varies by $\sim 10\%$ from pixel to pixel, the overall signal is at the fractional flux level of $\sim 10^{-4}$. Hence, with a signal-to-noise ratio of ~ 100 per pixel, one needs $\sim (100 \times 10^{-4})^{-2} = 10^4$ pixels to detect the cosmic deceleration signal at 1σ . More than this number of pixels is generally available per quasar, and so the signal is potentially detectable over a century for a single quasar. Ignoring systematic instrumental limitations, it should therefore be feasible to detect the cosmic signal only over a decade ($\Delta t_0 = 10 \text{ yr}$) by extending the sample to include $\sim 10^2$ such quasars. (The signal-to-noise ratio increases as the square root of the number of uncorrelated quasars.) The low H I column density absorbers ($\lesssim 10^{13} \text{ cm}^{-2}$) are believed to be associated with underdense regions, and hence their peculiar accelerations should be lower than the cosmic deceleration $\sim H_0 c$ by at least the ratio of the corresponding void size to the Hubble length. Changes in the H I absorption-line template caused by the evolution of structure in the intergalactic medium would result in negligible peculiar accelerations, $\sim (\delta v/c)\delta^{1/2} H_0 c$, except for the extremely overdense, and hence rare, regions that yield damped Ly α absorption.

Obviously, the efficiency of this technique can improve dramatically if a subset of all absorption lines (e.g., some metal lines) possess particularly sharp spectral features. Nevertheless, we should also make several cautionary remarks. First, extraction of cosmological parameters requires redshift binning that will reduce the signal-to-noise ratio per bin. Detection of the effect at several standard deviations would require an improvement by at least an order of magnitude in sensitivity over existing instruments. Systematic effects will ultimately limit the performance of any advanced instrumentation. In addition, the Ly α forest lines compose a somewhat inferior spectral template for the purpose of measuring velocity drifts compared to stellar lines, because of their lower abundance, their somewhat larger width, and the potential variability of their continuum source.

The other distant sources of interest are galaxies. The emission spectra of galaxies are merely a superposition of their stellar constituents. However, the rich emission- and absorption-line template that is employed for the detection of the slight reflex motion of individual stars (Butler et al. 1996) is degraded when incorporated into the galactic spectrum, owing to the broadening of the stellar lines by the velocity dispersion or

rotation of the galaxy (typically of order hundreds of km s^{-1}) and the resulting blending of some lines. On the other hand, the cumulative spectrum of a galaxy is much more stable than that of an individual star, because the variability due to convective or atmospheric motions that limits the radial velocity precision for individual stars is averaged out over the large number of uncorrelated changes in the stars that make up a galaxy. Galaxies are much more abundant, and hence compose a larger statistical sample, than quasars.

Since galaxies are typically ~ 2 orders of magnitude fainter than bright quasars, it is necessary to adopt time intervals $\Delta t_0 \sim 10^3$ yr in order to detect the cosmic signal in their spectra. While such time intervals might appear impractical on the scale of a human lifetime, they are accessible through the multiple images of a background galaxy that is gravitationally lensed by a foreground cluster of galaxies. The characteristic time delay between the two images produced by a singular isothermal sphere of a one-dimensional velocity dispersion σ is (Schneider, Ehlers, & Falco 1992, p. 244),

$$\Delta t_0 = \left(4\pi \frac{\sigma^2}{c^2}\right)^2 \frac{D_l D_{ls}}{c D_s} (1 + z_l) 2y, \quad (4)$$

where D_l , D_{ls} , and D_s are the angular diameter distances between the observer and the lens, the lens and the source, and the observer and the source, respectively; z_l is the lens redshift, and y is the unlensed source position in units of the critical radius of the lens. For the characteristic velocity dispersion of rich clusters $\sigma \sim (1000\text{--}1500) \text{ km s}^{-1}$, the delay is just in the range of $\Delta t_0 \sim 10^2\text{--}10^3$ yr required for detection of the cosmic deceleration signal. Moreover, the magnification of the background galaxy by the cluster would boost its observed flux and enhance the sensitivity to potential shifts in its spectral features. Comparison of the spectra of multiple images of the same galaxy, which are delayed relative to each other, should show the redshift difference predicted by equation (3). Unfortunately, the practicality of measuring this redshift difference is impeded by the need to collect all the light from the extended galaxy arclets within the observational aperture (this is made more difficult by the fact that lensing conserves surface brightness and stretches the area of the background galaxy on the sky); missing light from some parts of the galaxy could lead to a systematic velocity offset far greater than the cosmic signal. In addition, the cosmic signal is likely to be swamped by the difference in image redshifts due to a transverse peculiar velocity of the lens (Birkinshaw & Gull 1983); this change is of order the product of the deflection angle and the transverse velocity of the cluster, i.e., $\sim 3 \times 10^{-4} \times 10^{-3} c = 90 \text{ m s}^{-1}$.

Note that lensing cannot be employed to search for velocity shifts in the $\text{Ly}\alpha$ forest because the different images of a lensed quasar follow different spatial paths through the intergalactic medium on their way to the observer.

Finally, I should mention the somewhat speculative possibility of using radio sources, which offer exceptional frequency stability over a narrow bandwidth. Examples for such sources include powerful masers in galactic nuclei (Miyoshi et al.

1995), young extragalactic pulsars, or radio line emission/absorption from cold gas at high redshifts (Davis 1975; see also Davis & May 1978). Some of these sources (e.g., maser disks or pulsars in binary systems) might possess high peculiar accelerations intrinsically; however, the feasibility of detecting a signal with an amplitude as small as the cosmic deceleration from pulsar timing was already demonstrated in the Milky Way (Damour & Taylor 1991; Stairs et al. 1998). The faintness of these sources might restrict such measurements to the local universe but still provide a measurable signal—especially for an Ω_Λ -dominated cosmology.

4. CONCLUSIONS

Equation (3) implies that the change in the redshifts of extragalactic objects caused by the deceleration of the universe is not far out of reach of existing spectroscopic instrumentation. For example, two sets of Keck HIRES observations of the $\text{Ly}\alpha$ forest in the spectrum of a hundred $B \sim 16$ mag quasars, separated by a decade, might marginally allow for the statistical detection of the cosmic deceleration signal. The existence of some anomalously narrow line features in the $\text{Ly}\alpha$ forest can considerably improve the detection efficiency.

We find that peculiar accelerations caused by large-scale structure are typically orders of magnitude smaller than the cosmic deceleration signal ($\sim H_0 c$). Moreover, because of the random sign of their contribution, local effects would also average out in a sufficiently large sample of uncorrelated objects. In this sense, the cosmic deceleration signal is similar to the microwave background anisotropies, that despite their small amplitude (which posed a technological challenge for three decades) appear to carry fundamental information about the universe and not to be confused by contamination.

The cosmic deceleration signal should be isotropic and have the particular functional dependence on redshift predicted by equation (3). These characteristics can be used to identify its cosmic origin and to infer the values of H_0 , Ω_m , and Ω_Λ from it. Even though detection of the cosmic deceleration signal appears impractical at present, further advances in spectroscopic techniques and telescope size might allow it to be accessible in the future. Such a detection would complement the microwave anisotropy measurements, which also probe the geometry of the universe directly. It is useful to perform both experiments independently, since they cover different redshift regimes and could in principle even yield different results, because of the existence of a time-dependent cosmological constant or decaying dark matter. More importantly, the microwave background experiments will not be able to measure the values of the cosmological parameters with the desired precision if the primordial density perturbations were not predominantly adiabatic.

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