Constraints on Time-Dependent Dark Energy from the Flux Power Spectrum of the Lyman α Forest

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We present new calculations of the flux power spectrum of the Lyman α forest in order to investigate the effects of time-dependent dark energy on this statistic. We use a parameterized version of the dark energy equation of state and sample these parameters (w_0, w_a) from the allowed observational values as determined by the Planck Satellite. Each chosen (w_0, w_a) pair is then used in a high-resolution large-scale cosmological simulation run with the publicly available SPH code `GADGET-2`. From each of these simulations we extract synthetic Lyman α forest spectra and calculate the flux power spectrum at several different redshifts. These power spectra are then compared to available observational data.

Keywords: cosmology: dark energy — cosmology: theory — methods: numerical

1. Introduction

Given the compelling evidence for cosmic acceleration, as well as the unknown nature of the mechanism behind it, it is imperative to explore every possible probe of the nature of dark energy. In this talk we study the feasibility of using the flux power spectrum of the Lyman α (Lyα) forest as a probe for constraining the time-dependence of dark energy. The motivation for this is as follows. The cosmic web is composed of three major types of structures: clusters, filaments, and voids. Since dark energy possesses a negative energy density, it is thought that the effects of dark energy, with respect to the cosmic web, should be most apparent on the morphology of voids. The absorbers responsible for the Lyα forest should reside primarily in the clusters and filaments. However, along a given line of sight (LOS), these absorbers will be separated by the voids. As such, the separation of these absorbers in redshift space should act as a tracer of the evolution of the voids. Additionally, studying the Lyα forest is an independent and complimentary approach to searches based on the SNIa redshift-distance relation, the CMB, BAO, ISW, and gravitational lensing, and one that has received comparatively little attention in the literature.

1.1. *The Lyman α Forest*

The Lyman α forest is the dense collection of *HI* Lyα absorption lines in spectra of distant quasars (QSOs). Each of these lines is imprinted on the spectrum by a particular absorber at a particular intervening redshift. The cosmic expansion then causes each of these lines to redshift away from the Lyman α rest wavelength of ≈ 1216Å in accordance with the redshift of the absorber. A coherent picture of the absorbers responsible for causing the Lyα forest did not arrive until hydrodynamical simulations showed that the Lyα forest was caused by fluctuations in the density field along the LOS to the QSO, thereby providing a glimpse of the cosmic web.[1–4]

By treating the Lyα forest as a fluctuating Gunn-Peterson approximation (FGPA),[5]) it has been shown[6] that there exists a power-law relation between the temperature and the density of the gas in the inter-galactic medium (IGM):

$$T = T_0(1+\delta)^{\gamma-1}, \tag{1}$$

where T_0 is the temperature of the IGM at the mean density and at a given redshift and $\gamma-1$ gives the slope of the power-law. In low-density, still mildly linear regions of interest, the gas roughly follows the dark matter distribution.[8] All of these factors combine to make the Lyα forest a unique probe for exploring cosmology in the redshift range from $2 < z < 5$. In this redshift range the Lyman α forest can complement other cosmological probes such as the CMB.[9].

1.2. *Motivation*

The only possible observable difference between various dark energy models is in how their energy-densities change in time. As such, a first step is to determine whether or not the dark energy changes in time at all.

However, there is a degeneracy between the various allowed dark energy models wherein they all must converge to have a present day value of $w(z=0) \approx -1$ in order to be consistent with observations, which, when combined with the fact that dark energy seems to have only recently come to dominate. This makes model discrimination difficult. The degeneracy is stronger at lower redshifts, which illustrates the importance of high-redshift observations as well as observations that span a large redshift range in breaking this degeneracy. The Lyman α forest possesses both of these qualities. No one observational probe is capable of breaking this degeneracy on its own and so we must rely on a combination of probes.[10] While identifying the exact model for dark energy is not feasible at this time, both tightening the constraints as well as exploring different avenues for model discrimination is a first step towards determining if dark energy is constant or dynamical in time.

To this end, we consider the usefulness of the Lyman α forest as a probe of dark energy. This idea has been explored previously[11], however they did not consider fully dynamical dark energy, instead restricting themselves to various values of constant w. Additionally, a semi-analytic treatment has been used[11] in the study of the Lyα forest. We expand upon previous work by making use of high-resolution N-body simulations, from which we extract synthetic Lyα spectra as well as by using fully dynamical models of dark energy that probe the currently allowed parameter space for (w_0, w_a). Here we wish to clarify if the dark energy is constant or dynamical in time and whether or not the Lyman α forest can be used as a probe to make this distinction.

2. Simulations

Our simulations were run with the publicly available smoothed-particle-hydrodynamics (SPH) code `GADGET-2`[12]. Our version of `GADGET-2` has been heavily modified[13,14] so as to include star formation, UV heating, radiative cooling, and stellar feedback from Type Ia SN, Type II SN, and AGB stars.

Simulating the Lyα forest requires very high resolution. It has been suggested[15] that a resolution of $\approx 40h^{-1}$kpc in a box of size $L \approx 40h^{-1}$Mpc is needed in order to adequately resolve the structure of the Lyα forest and achieve convergence for the power spectrum. With these requirements in mind, we simulated 1024^3 dark matter particles in a box of length $40h^{-1}$ comoving Mpc.

We ran three simulations: one with the cosmological constant and two with dynamical dark energy . The two dynamical models were chosen such that their parameters were as close to the edges of the allowed 95% confidence range for the (w_0, w_a) parameter space as given by[16]. We chose to be near the fringes of the allowed parameter space in the hope that by using the largest allowed differences in both w_0 and w_a between our models we would be working with the models that have the largest observable difference between them. Each of our three simulations was started from the same initial conditions and evolved from $z = 49$ to $z = 2.2$. Our initial conditions were generated using the publicly available second-order Lagrangian perturbation theory code `2LPTIC`[17]. We generated snapshots of each simulation at $z = 4.2, 3.8, 3.0, 2.7$, and $z = 2.2$. We chose these particular redshift values because they correspond to the redshifts at which there is observational data for the Lyα forest flux power spectrum from multiple authors. This allows us to compare our predicted results with a range of observations. The publicly available version of `GADGET-2` assumes that dark energy arises from the cosmological constant. Nevertheless, modifying `GADGET-2` to include the effects of dynamical dark energy was relatively straight forward. For reasons of speed, this was implemented using a look-up table that was generated at the beginning of the run.[18].

2.1. *Generation of Synthetic Spectra*

All of our simulations were performed with dark matter particles only for reasons of speed. Calculating a synthetic spectrum, however, requires knowledge of the temperatures, densities, and *H I* neutral fractions for each of the simulation particles. Since these are not properties of dark matter particles in `GADGET-2`, we calculate these quantities in post-processing. All of the methods described here, except for the density calculation, are described in previous work.[3,19].

The densities were computed by making use of `GADGET-2`'s density calculation[12] adapted to work on dark matter particles. Ultimately, we deduce a power spectrum characterizing the statistical redshift intervals between Ly-α absorbers.

We find that there is at most a weak dependence upon the time dependence of dark energy by this statistical method.

3. acknowledgments

This work was supported in part by by the U.S. Department of Energy under Grant DE-FG02-95-ER40934.

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