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Cosmology with Quasar Pairs

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Abstract

The Ly-α forest represents a map of the H I opacity of the intergalactic medium, and it can be used as a cosmological probe over the redshift range $0 < z < 6$. Quasar pairs and groups can provide measures of the coherence scale and the topology of the absorbing gas on scales of $\sim 1\ h_{100}^{-1}$ Mpc. The relation between the transverse and line-of-sight flux correlations at z = 2-3 gives sensitivity to spatial geometry, including the presence of a vacuum energy term. Hydrodynamic simulations show that the H I is related in a well defined way to the underlying density field.

1.1 Quasars as Probes

The "forest" of absorption lines blueward of Ly-α emission in quasar spectra are of growing value as cosmological tools. The absorption is caused by diffuse gas in the intergalactic medium (IGM) that is highly ionized. The small neutral fraction imprints a continuously varying opacity of the quasar continuum, usually called the fluctuating Gunn-Peterson effect (Bahcall & Salpeter 1965; Gunn & Peterson 1965). In hierarchical models of structure formation, the absorbers trace matter that has formed into mildly nonlinear sheets and filaments (see Rauch 1998, for a review).

This picture was strongly supported by the earliest hydrodynamic simulations of the universe (Cen et al. 1994). Hydro simulations can reproduce the basic properties of the absorbers, such as the column density distribution, the Doppler parameters, and the initially rapid cosmic evolution in number density (Hernquist et al. 1996; Theuns et al. 1998; Davé et al. 1999). Since hydrodynamic simulations do not yet have the resolution to model scales on which the universe is homogeneous, they have been valuably augmented by analytic studies, which are better able to map large regions of physical and parameter space (Gnedin & Hui 1996; Bi & Davidsen 1997). The combination of theory and simulation has allowed the Ly-α forest to be used for measures of the baryon density (Rauch et al. 1997), the matter density (Weinberg et al. 1999), the equation of state of the IGM (Shaye et al. 2000), and the power spectrum of mass fluctuations (Croft et al. 1998; Hui et al. 2001).

1.2 Observations and Simulations

Research on Ly-α absorption has led to some impressive successes in observational cosmology, but there are important methodological differences between observational studies of quasar spectra and the data extracted from simulations. Observers traditionally fit discrete spectral features (with Voigt profiles if the thermal and bulk gas motions are resolved, and with Gaussians if the features are dominated by the instrumental profile) with respect to a varying continuum that is unknown *a priori*. Quasar pairs and groups offer long 1D sightlines but very sparse sampling if 3D "tomography" of the gas distribution is the goal. It is also still routine for observers to fit absorption lines and interpret line coincidences and anti-coincidences in terms of Bayesian models, where the absorbers have simple geometries like spheres or disks (e.g. D'Odorico et al. 1998; Aracil et al. 2002). These simple models are a very poor representation of the complex web of structure seen in the simulations.

Hydrodynamic simulations provide a detailed view of baryons and dark matter in the universe on scales up to $\sim 50\ h_{100}^{-1}$ Mpc, although large scale structure on scales larger than $5-10\ h_{100}^{-1}$ Mpc are aliased and huge computational resources are required to run these simulations to $z = 0$ for a range of cosmological models. Excellent sampling of the 3D gas distribution is provided by the roughly 10^5 independent spectra that can be extracted from a simulation. Opacity is measured with respect to a known continuum and with high enough resolution that complex gas dynamics are imprinted into the spectral features (to the extent that a Voigt profile is often a poor model). Simulators have long been aware that the approach of selecting absorption "lines" will not use the full information presented by a continuous map of opacity. Procedures that use the full spectrum are preferred, such as the flux probability distribution function, the power spectrum, and the correlation function (McDonald et al. 2000). These procedures can readily be extended to multiple lines of sight (Viel et al. 2002), but they are non-trivial to apply to real quasar spectra.

1.3 Large-Scale Structure

Non-lensed quasar pairs with appropriate angular separation (roughly $30-300$ arcseconds) tend to be rare and often faint. Absorption line studies have detected line correlations on proper transverse scales of 0.2 to $\sim 1\ h^{-1}$ Mpc over the redshift range $0.5 < z < 2.5$ (Dinshaw et al. 1994, 1998; D'Odorico et al. 1998; Petitjean et al. 1998; Liske et al. 2000). The addition of a third quasar allows the distinction to be made between absorbing filaments and sheets (Crotts & Fang 1998; Young, Impey & Foltz 2001). The number of quasar pairs with arcminute separations and similar redshifts is very limited. This situation is not directly improved by the SDSS due to the relatively shallow limit of the spectroscopic survey (Richards et al. 2002). The requisite number of pairs for sensitive cosmological measurements will come from the 2dF QSO Redshift Survey (Croom et al. 2001), augmented by spectroscopy of candidates selected from SDSS photometry (Newberg et al. 1999).

We have compared data from several pairs at $z \sim 2$ with spectra extracted randomly from a hydrodynamic cosmological simulation using smoothed particle hydrodynamics (Katz, Weinberg & Hernquist 1996; Petry et al. 2002). The line-fitting software provides a robust and reliable way to identify "high peaks" in the absorption opacity, and it has been tested on real and simulated spectra covering a wide range in resolution and signal-to-noise. Absorber pairs are formed by requiring a symmetric match between the two sightlines. We detect coherence in the simulations and in the data on transverse scales of $250\ h_{100}^{-1}$ kpc at $z = 2$. We also compare the two-point correlation function (TPCF) for the flux to the TPCF for discrete absorber pairs. The two statistics yield consistent results. Future work will use these techniques to compare Ly-α coherence towards pairs and groups of quasars to the cosmic web of large scale structure extracted from simulations.

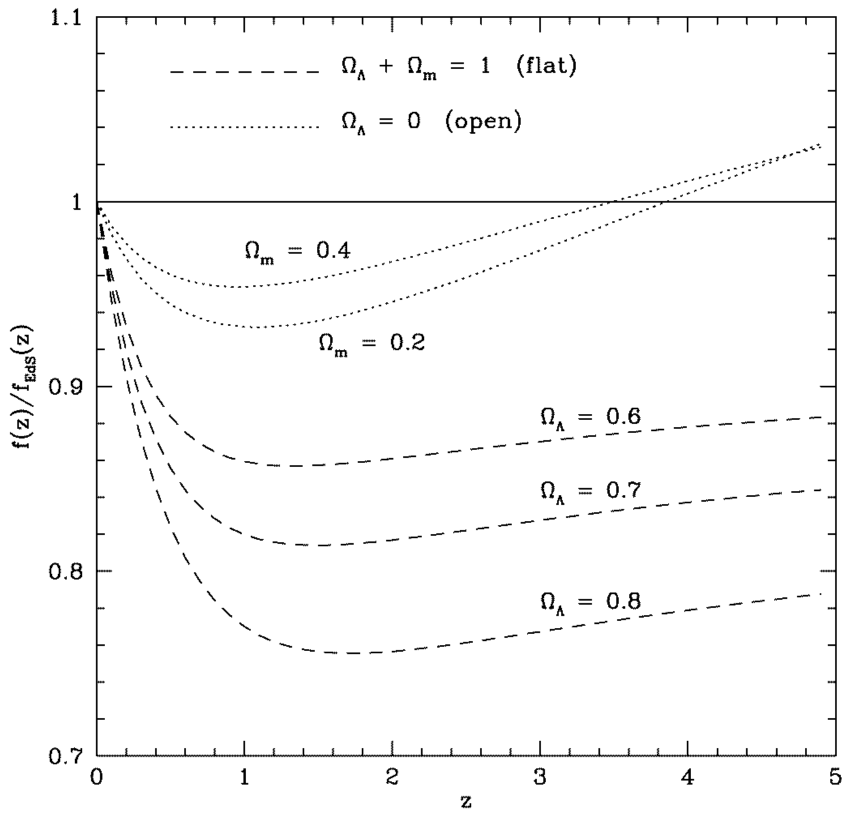

Fig. 1.1. The generic effects of a positive cosmological constant are shown in this figure from Coles & Lucchin (1995). Relative to an open model or a flat, matter-dominated model, a model with Λ has a higher age and a larger comoving distance at a given redshift. For flat models, the angular size at a given redshift is larger when there is a cosmological constant. With absorption along two sightlines, the two observables are redshift separation along each sightline and angular separation, where the perpendicular velocity separation encodes the sensitivity to the cosmological constant.

1.4 The Cosmological Constant

The two primary constituents of the universe — dark matter and vacuum energy — are not understood in terms of fundamental physical theory. In other words, the standard model of particle physics provides no explanation why these two microscopic components of the universe should govern the global dynamics of the expansion. While there are plausible weakly-interacting particle relics that could give rise to a critical density of dark matter, the apparent fine-tuning of the vacuum energy is a deep mystery (Weinberg 1989). The "concordance" cosmology depends critically on the fact that the dimness of high redshift supernovae is an indication of cosmic acceleration (Turner 1999; Riess et al. 1998; Perlmutter et al. 1999). It is very desirable to have a test for vacuum energy that does not depend on the assumption that Type Ia supernovae are not subject to evolutionary effects.

The Alcock & Pacynski (1979) test relies only on the fact that tracers of space are isotropic over a cosmic average. No assumption of standard candles is involved. Spatial geometry is derived from the different mappings of redshift distance and angular size distance. However, the cosmological signature must be separated from peculiar velocities and redshift-space distortions, which affect the correlations in redshift. The Ly-α forest of close quasar pairs is an ideal laboratory for this test, since the absorbers trace small density enhancements over the cosmic mean, so the departures from the Hubble flow can be modeled to first order by linear theory (Hui, Stebbins & Burles 1999; McDonald 2002). The substantial coherence length of the absorption coupled with the huge numbers of new quasars being found by the Sloan and 2dF surveys mean that the test is now tractable given sufficient large telescope time. Thirty to forty quasar pairs with angular separations of a few arcminutes are required for a measurement of Λ (McDonald 2002).

1.5 Simulations and Prospects

We have analyzed Ly-α absorption spectra drawn from a cosmological SPH simulation (Davé et al. 1999) to investigate the feasibility of detecting the cross-correlation in the forest for separations of $1-5'$ in the range $2.1 < z < 2.6$. We find a measurable signal for proper separations of more than 1 h_{100}^{-1} Mpc, which corresponds to greater than $3'$ at $z = 2.73$. Interestingly, we find that the variance in the measured correlation in different lines of sight is only weakly dependent on the signal to noise of the spectra (excluding as yet uninvestigated errors in the continuum fit) for $\mathrm{S/N} \gtrsim 10$. The strongest absorption features dominate the cross-correlation signal, while the observed dispersion is actually due to the variance of the absorber population itself. This is encouraging — relatively modest S/N is required, so spectra of sufficient quality can be obtained in a few hours on the 6.5m Magellan and MMT telescopes for the typically faint ($V \gtrsim 20.5$) pairs. We will analyze similar cosmological simulations with a range of world models (typically large dark matter simulations calibrated by smaller SPH simulations) to model the effects of the redshift-space distortions on the signal of spatial geometry.

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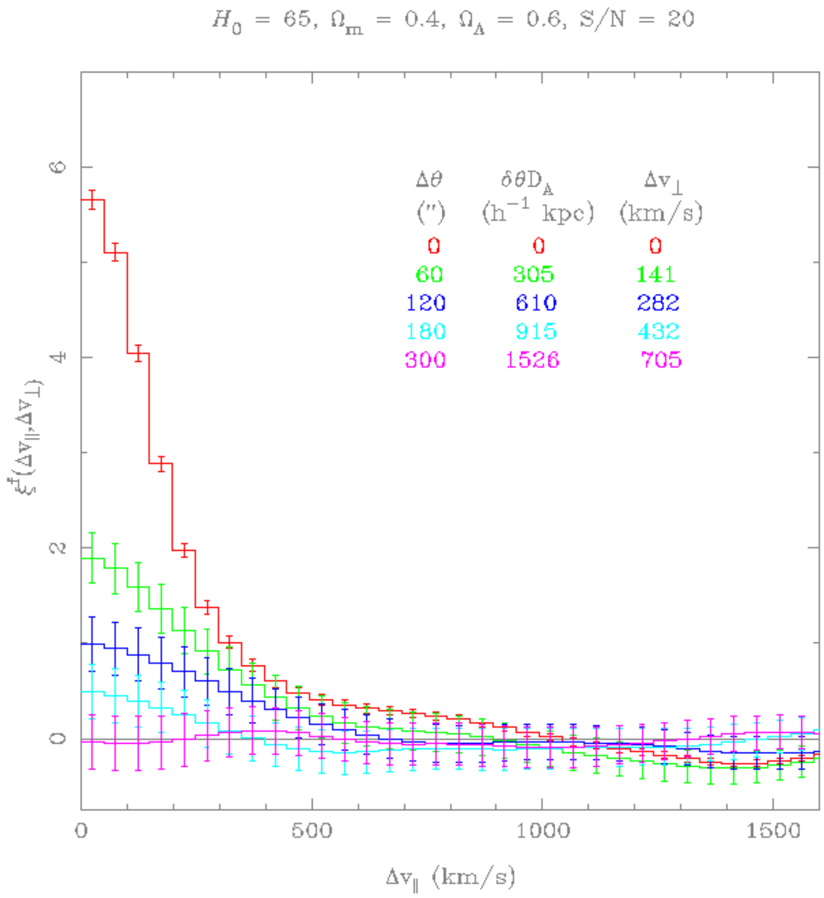

Fig. 1.2. The auto and cross-correlation functions for 1000 paired lines of sight through an SPH simulation, binned to ∼1.5 Å resolution and degraded to S/N = 20. This total path length is roughly equivalent to 35 observed pairs. Thus, the correlation signal for separations of $3'$ and less is readily measurable in our observational experiment.

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