Transverse and Longitudinal Correlation Functions in the Intergalactic Medium

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The Intergalactic Medium can be studied using the imprint left in the spectra of background quasars, the so-called Lyman-α forest. The correlations between absorption features observed along the lines of sight to the quasars have been studied to derive information on the clustering properties of the IGM structures. Very few observations have been performed so far of the correlation of the absorption along two different lines of sight separated by a few arcminutes in the sky. The comparison of the correlation functions along the line of sight (longitudinal direction on a velocity scale) and in the perpendicular direction (on an angular scale) can be used to constrain the geometry of the Universe. We have recently completed a study of the transverse and longitudinal flux correlation functions of the Lyman-α forest in quasar absorption spectra at $z \sim 2.1$ from VLT-FORS and VLT-UVES observations of a total of 32 pairs of quasars with separations in the range $0.6 < \theta < 10$ arcmin and found a correlation signal up to 3–5 arcmin.

The numerous H I absorption lines seen in the spectra of distant quasars, the so-called Lyman-α forest, contains precious information on the spatial distribution of neutral hydrogen in the Universe. Unravelling this information from individual spectra has for a long time proven difficult and ambiguous. Studies of the correlation of the Lyman-α forests observed in the two spectra of QSO pairs have been instrumental in measuring the spatial extent of absorbing structures. Significant correlation between absorption spectra of adjacent lines of sight toward quasars exists for separations of a few to ten arcmin suggesting a size or better a coherence length of the structures larger than 500 h_{70}^{-1} kpc (e.g. Smette et al. 1995; Crotts and Fang 1998; Aracil et al. 2002) and a non-spherical geometry of the absorbing structures (Rauch et al. 2005). On even larger scales, Williger et al. (2000) still find evidence for an excess of clustering on 10 Mpc scales.

The picture of the Lyman-α forest arising from density fluctuations in a warm photoionised Intergalactic Medium distributed as expected in a CDM model explains the statistical properties of individual QSO absorption spectra very well. Most of the baryons are located in filaments and sheets which are only overdense by factors of a few and produce absorption in the column density range $10^{14} < N_{HI} < 10^{15}$ cm^{-2} at $z \sim 2$. On the other hand, most of the volume is occupied by underdense regions that produce absorption with $N_{HI} < 10^{14}$ cm^{-2}. Analytical calculations and numerical simulations of the spatial distribution of neutral hydrogen in ΛCDM models are also able to reproduce the large observed transverse correlation length of the Lyman-α forest in the absorption spectra of QSO pairs (e.g. Rollinde et al. 2003).

As pointed out by several authors a comparison of the transverse correlation to the correlation observed along the line of sight, can be used to carry out a variant of the Alcock and Paczyński (1979) test to put constraints on the geometry of the Universe (e.g. Mc Donald 2003). This provides strong motivation for an accurate measurement of the transverse correlation function.

We have obtained spectra for a very large sample of QSO pairs: 26 pairs with separations in the range 0.6–4 arcmin (corresponding to $\simeq 0.2$ to 1.4 h^{-1} Mpc proper at $z = 2.1$ for $\Omega_m = 0.3$, $\Omega_\Lambda = 0.7$) and six pairs with separations in the range 5–10 arcmin. The results of the survey are published in Coppolani et al. (2006).

Observations

The first release of the 2dF quasar survey has significantly enlarged the number of known quasar pairs with arcmin separation (Outram, Hoyle and Shanks 2001). We have selected pairs with the following criteria: (1) the separation of the two quasars should be in the range 1–4 arcmin where the correlation is expected to be strong; (2) the quasars should be brighter than $m_V = 20.30$ to keep observing time in reasonable limits; (3) the emission redshifts of the two quasars should be larger than $z \sim 2.1$ to increase the wavelength range over which high S/N ratio can be obtained (FORS is not sufficiently sensitive below 3 500 Å); (4) the redshift difference should be smaller than $\Delta z \sim 0.5$ (for most of them 0.3) to maximise the wavelength range over which correlations can be studied.

There are 22 quasar pairs in the 2dF survey which meet our criteria of which we observed 20. Twelve previously known pairs have been added to this sample. The spectra of the quasars were obtained with FORS1 and 2 mounted on VLT UT2 and UT3 using grism GR630B and a 0.7 arcsec slit. The final spectral resolution was $R = 1400$ or FWHM = 220 km s^{-1} at 3 800 Å. The exposure times have been adjusted in order to obtain a typical signal-to-noise ratio of ~ 10 at 3 500 Å. At $\lambda \sim 4 500$ Å the S/N ratio is usually larger than 70. Typical observed spectra of QSO pairs are shown in Figure 1.

To calculate the longitudinal correlation function we also used the data from the Large Programme "The Cosmic Evolution of the IGM" which has produced a sample of absorption spectra of homogeneous quality suitable for studying the Lyman-α forest in the redshift range 1.7–4.5. The spectra of the LP were taken with VLT-UVES and have high resolution (R $\sim$ 45 000) and high signal-to-noise ratio. (30 and 60 per pixel at respectively 3 500 and 6 000 Å.)

Numerical simulations

We used two numerical simulations to estimate the errors and the effect of redshift distortion and of the thermal state of the gas on the correlation functions: a

large-size dark-matter only simulation and a smaller-size full hydrodynamical simulation. For both simulations we assume parameters consistent with the fiducial concordance cosmological model $\Omega_\Lambda = 0.7$, $\Omega_m = 0.3$. The hydrodynamical simulation of 40 Mpc box-size and dark-matter only simulation of 100 h^{-1} Mpc box-size are used to catch both the statistical aspects and the effect of gas physics. The large box-size of the dark-matter only simulation ensures a sufficient statistical sampling on large scales where thermal effects and pressure effects, which are modelled approximately in this simulation, are less important. The hydrodynamical simulation is better suited for investigating the effects of thermal broadening and redshift distortions which are more relevant on small scales. The 40 Mpc box-size of the hydrodynamical simulation offers the best compromise between box-size and resolution.

The observed correlation functions

We define the flux correlation function, $\xi_f(\theta, \Delta v)$, as in Rollinde et al. (2003). In the following we will use $H_0 = 70$ km/s/Mpc, $\Omega_m = 0.3$, $\Omega_\Lambda = 0.7$ to relate scales in redshift space with angular scales. With these parameters $\Delta v = 100$ km s^{-1} corresponds to ~ 1 arcmin at $z = 2$. The observed correlation functions depend strongly on the spectral resolution of the absorption spectra unless the width of all spectral features is fully resolved.

In Figure 2 we show the observed transverse correlation function derived using the 32 pairs of our sample. Each point on this figure corresponds to one pair. The measurement for each quasar pair, $\xi(\theta_i) \equiv \xi_f(\theta_i; \Delta v = 0)$, is shown as a small solid triangle at the angular separation of the pair, θ_i. The transverse correlation is clearly detected on scales < 4 arcmin. If we merge the two bins between 3 and 4 arcmin, the correlation is detected at about the 3σ level.

We have calculated the longitudinal correlation function (the correlation measured along the line of sight to the quasar) from the 58 FORS spectra in the sample at a mean redshift z ~ 2.1. We also have estimated the longitudinal correlation function measured from the high-

resolution spectra obtained in the course of the UVES-VLT Large Programme. The two correlation functions agree very well after the high-resolution VLT-UVES spectra is convolved with a Gaussian filter of FWHM = 220 km s^{-1} to take into account the difference in resolution between the UVES and FORS spectra.
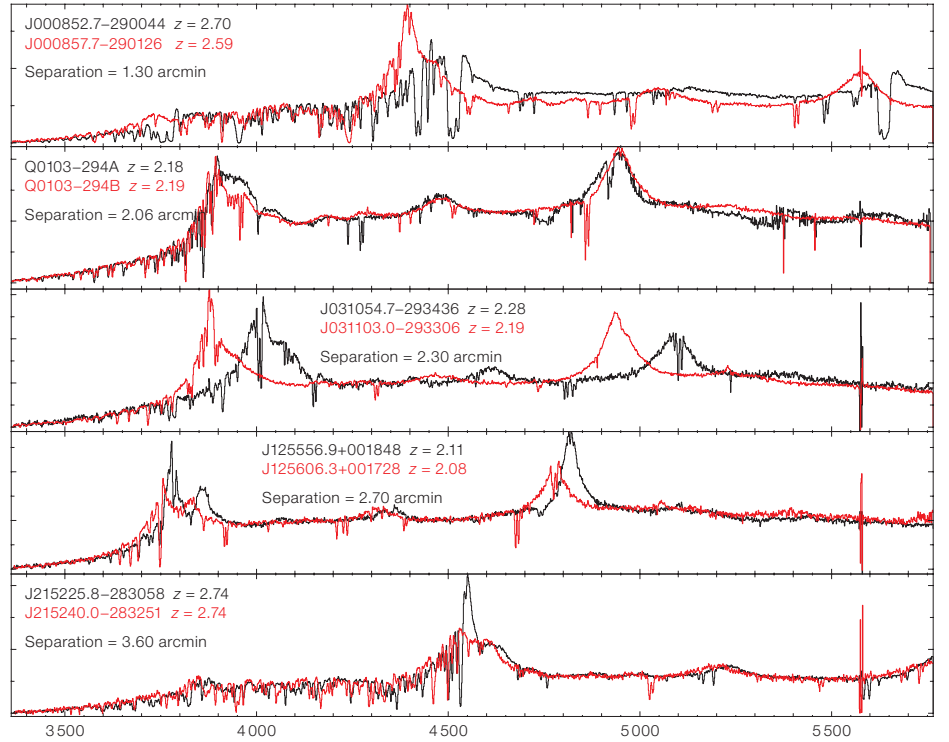

Figure 1 (Above): Typical observed spectra of QSO pairs in order of increasing right ascension. QSO names, emission redshifts and angular separations are given in the top-left corner of each sub-panel.
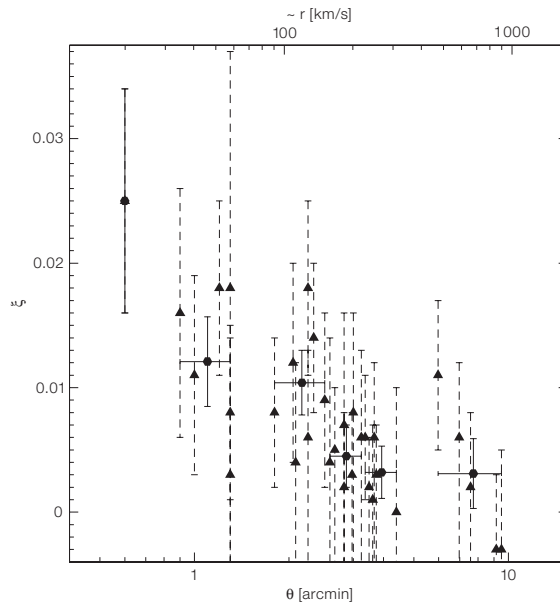

Figure 2 (Left): The observed transverse correlation coefficient for individual pairs (black triangles, dashed error bars) and a binned estimate of the transverse correlation function (solid error bars). Note that the first bin at the smallest separation contains only one measurement.

Comparison of observed and simulated correlation functions

The ability of ΛCDM models to reproduce the longitudinal correlation function of the Lyman-α forest has been demonstrated by many authors (e.g. Rollinde et al. 2003) and the same is true for our simulations. The curves from the hydro-

dynamical simulation in Figure 3 for $z = 2$ and $z = 3$ nicely bracket the observed correlation function obtained from the high-resolution data with a median red-shift of $z = 2.39$.

The transverse correlation contains precious direct information on the physical size/coherence-length of the absorbing structures as it is less affected by redshift space distortions than the longitudinal correlation function. Furthermore, a comparison of the longitudinal and transverse correlation functions can – at least in principle – strongly constrain cosmological parameters in particular Ω_Λ.

The thick solid curve in Figure 4 shows our estimate of the transverse correlation function from the full hydrodynamical simulation at $z = 2$. It agrees well with our measurement of the observed transverse correlation function (mean redshift ~ 2.1).

Despite the larger sample (about three times more pairs at $\theta < 3$ arcmin than in Rollinde et al. 2003) and the correspondingly smaller errors, we cannot yet distinguish between different values of Ω_m. However, the result shown here is very encouraging as it shows that clustering signal is present up to about 4 arcmin, consistent with the predictions of ΛCDM models.

Metal absorption systems

Our sample of quasar pairs is also well suited to study the spatial distribution of the gas responsible for the associated metal absorption in QSO spectra. We have selected after identification a sample of 139 C IV systems distributed over a redshift path $\delta z = 38$, corresponding to a density of 3.7 systems per unit redshift. We apply the Nearest-Neighbour method, as described in Aracil et al. (2002) to the corresponding list of C IV systems.

We do not find any statistically significant signal of correlation in the transverse direction. This is consistent with the models by Scannapieco et al. (2006) who have shown that, at $z \sim 3$, the longitudinal C IV correlation function is consistent with a model where C IV is confined within bubbles of typical radius ~ 2 Mpc comoving surrounding halos of mass ~ 10^{12} M$_\odot$. At
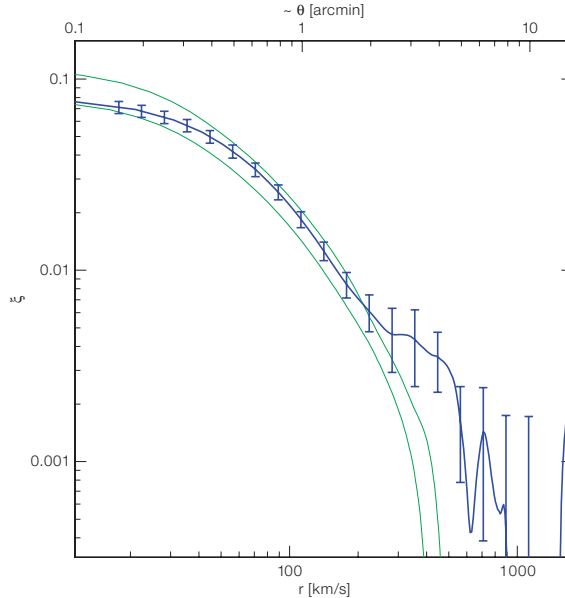

Figure 3: The observed longitudinal correlation function from the high-resolution UVES spectra (thick solid curve) compared to the longitudinal correlation function as measured in the full hydrodynamical simulation at $z = 2$ (lower thin curve) and $z = 3$ (upper thin curve), respectively.
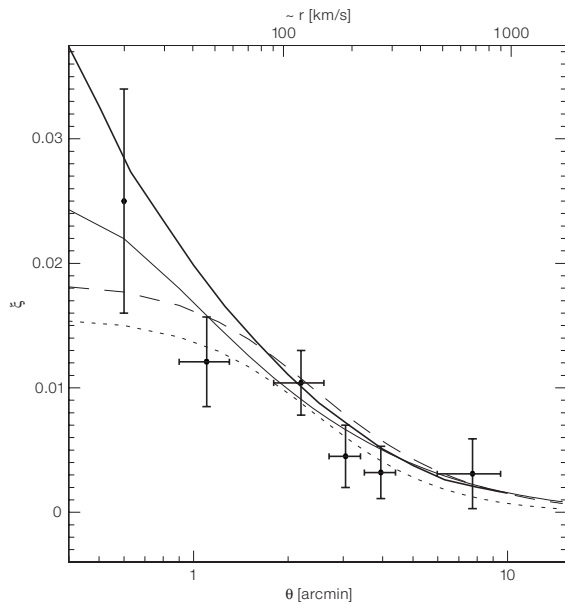

Figure 4: The binned estimate of the observed transverse correlation function (solid error bars) is shown together with the estimate of the transverse correlation function from the full hydro-simulation (thick solid curve) and linear predictions for $\Omega_m = 0.1$, 0.3 and 1 (thin solid, dashed and dotted lines respectively, assuming a flat Universe: $\Omega_\Lambda + \Omega_m = 1$). The linear theory predictions are normalised to reproduce the longitudinal correlation function at large scales.

this redshift, this corresponds to a separation of about 2 arcmin, smaller than the median separation in our sample.

However, there is a possible small excess of clustering of C IV systems on scales smaller than 5 000 km s^{-1}. This scale is larger than the typical correlation length, of about 1 000 km s^{-1}, seen in the longitudinal correlation function of C IV systems (e.g. Scannapieco et al. 2006). This is due to an excess of associations in the velocity bin $\Delta v \sim 4\,000$ km s^{-1}. However, the corresponding C IV associations are located in the peculiar field containing the

quartet Q 0103-294A&B, Q 0102-2931 and Q 0102-293 (all four quasars are separated by less than 10 arcmin). Along these lines of sight the density of C IV systems is 6.4 per unit redshift and the number of coincidences within 4 000 km s^{-1} is about twice larger than the mean density of coincidences in the overall sample. In addition, there is no C IV system between $z = 1.955$ and 2.051, a redshift range over which the H I absorption in front of the quartet is much reduced (Rollinde et al. 2003). Note also that the correlation between the Lyman-α forests of Q 0102-2931 and Q 0103-294B,

two quasars of the group with ~ 6 arc-min separation, is measured to be quite high (ξ = 0.011).

A similar overdensity of C IV systems has been observed in the field of Tol 1037–2704 (e.g. Jakobsen et al. 1986) and has been interpreted as being due to the presence of a supercluster. The dimensions of this supercluster would be at least 80 and 30 h^{-1} Mpc along and perpendicular to the line of sight, respectively. To our knowledge no deep imaging of these fields exist and it would be very interesting to search for possible concentrations of galaxies.

Future prospects

We have detected the transverse correlation of the intergalactic medium at the 3σ level up to separations of about 3–5 arcmin. The shape and correlation length of the transverse correlation function of the absorbing gas is in good agreement with expectations for absorption by density fluctuations in the warm photoionised Intergalactic Medium as described in CDM-like structure formation models. Our measurement is thus an important further independent confirmation that the Lyman-α forest is indeed caused by the filamentary and sheet-like structures of the cosmic web predicted by these models. In agreement with predictions of previous theoretical studies we find that our sample is still too small to obtain significant constraints on cosmological parameters. The improved errors of our larger sample compared to the sub-sample of Rollinde et al. (2003) suggest however that meaningful constraints on Ω_Λ can be obtained. For this, a larger sample and a careful analysis of the systematic uncertainties with a large suite of full hydrodynamical simulations are necessary. Mc Donald (2003) estimated that this requires a sample of 13$(\theta/1')^2$ pairs on scales up to 10 arcmin.

In addition, our results open the prospect to reconstruct the 3D density field directly (see Pichon et al. 2001). For this a network of lines of sight in the same field should be observed. Intermediate and/or low spectral resolution is sufficient but the distance between lines of sight is crucial and should be smaller than about 5 arcminutes.

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Extrasolar Planets and Brown Dwarfs: A Flurry of Results

Three ESO press releases on extrasolar planets and brown dwarfs in the last few months testify to the pace of activity in this field at the moment. They are summarised briefly here, and are available in complete form on the ESO website (PR 19/06, 28/06, 29/06).

Planetary-Mass objects surrounded by discs

Two new studies show that objects only a few times more massive than Jupiter are born with discs of dust and gas, the raw material for planet making. This suggests that miniature versions of the solar system may circle objects that are some hundred times less massive than our Sun.

For a few years it has been known that many young brown dwarfs, 'failed stars' that weigh less than eight per cent the mass of the Sun, are surrounded by a disc of material. This may indicate that these objects form the same way as did our Sun. The new findings confirm that the same appears to be true for their even smaller cousins, sometimes called planetary-mass objects or 'planemos'. These objects have masses similar to those of extrasolar planets, but they are not in orbit around stars – instead, they float freely through space.

"Now that we know of these planetary-mass objects with their own little infant planetary systems, the definition of the word 'planet' has blurred even more", adds Ray Jayawardhana (University of Toronto, Canada), lead author of the study. "In a way, the new discoveries are not too surprising – after all, Jupiter must have been born with its own disc, out of which its bigger moons formed."

Unlike Jupiter, however, these planetary-mass objects are not circling stars. In their study, Jayawardhana and Ivanov (ESO) used the VLT and NTT to obtain optical spectra of six candidates identified recently by researchers at the University of Texas at Austin. Four of the six turned out to have masses between five to 15 times that of Jupiter. All four of these objects are 'newborns', just a few million years old, and are located in star-forming regions about 450 light years from Earth. They show infrared emission from dusty discs that may evolve into miniature planetary systems over time.

In another study, Subhanjoy Mohanty (Harvard-Smithsonian Center for Astrophysics, CfA), Ray Jayawardhana (University of Toronto), Nuria Huelamo (ESO) and Eric Mamajek (also at CfA) used the VLT and NACO to obtain images and spectra of a planetary-mass companion