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**Constraints on dark energy and quintessence with a comoving standard ruler applied to 2dF quasars**

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**Abstract.** Structures on very large scales (> 100 Mpc) have negligible peculiar motions, and are thus roughly fixed in comoving space. We looked for significant peaks at very large separation in the two-point correlation function — corrected for redshift selection effects — of a well covered subsample of 2378 quasars of the recently released 10k sample of the 2dF quasar survey. Dividing our sample in three redshift intervals, we find a peak at \( \simeq 244 h^{-1} \) Mpc, which is perfectly comoving for a restricted set of cosmological parameters, namely \( \Omega_m = 0.25 \pm 0.15 \) and \( \Omega_\Lambda = 0.65 \pm 0.35 \) (both at 95% confidence). Assuming a flat Universe, we constrain the quintessence parameter \( w_Q < -0.35 \) (95% confidence). We discuss the compatibility of our analysis with possible peaks in the power spectrum.

1 Introduction

The quest for the parameters of the primordial Universe has significantly advanced in the last 10 years. There is a general agreement that \( \Omega_m \simeq 0.3 \), for example from the internal kinematics of clusters and groups \cite{11}, from the gas fraction in clusters \cite{20} and groups \cite{6}. Supernovae used as standard candles have led to \( \Omega_\Lambda > 0 \), with a degeneracy with \( \Omega_m \). Finally, the scales of the angular fluctuations of the cosmic microwave background (CMB) lead to a nearly perfectly flat Universe \( \Omega_m + \Omega_\Lambda = 1 \). The combination of constraints from supernovae and the CMB recovers \( \Omega_m \simeq 0.3 \) (with \( \Omega_\Lambda \simeq 0.3 \)).

We present below a measurement of the cosmological parameters, with a fairly new technique based upon using very large scale structures (> 100 Mpc in size) as comoving standard rulers.

2 Very large-scale structures should follow the Hubble flow

Very large-scale structures should follow the Hubble flow. The rms peculiar velocity within a ball of radius \( R \) is given by

\[
\langle v_{\text{rms}}^2(R) \rangle = \frac{1}{2 \pi^2} (H f)^2 \int_0^\infty \tilde{W}^2(k R) P(k) \, dk ,
\]

(1)
where for $\Omega_\Lambda = 0$ or for flat Universes, $f \simeq \Omega_m^{0.6}$, while $P(k)$ is the primordial density fluctuation spectrum and $\tilde{W}(x) = 3(\sin x - x \cos x)/x^3$ is the Fourier transform of the top-hat smoothing kernel. Eq. (1) leads to a present-day value $v_{\text{rms},0} < 330 \text{ km s}^{-1}$ for $R > 100 h^{-1} \text{ Mpc}$. Since the peculiar velocity increases with time, one simply finds that the peculiar motion satisfies $\delta R < v_{\text{rms},0} t_0 = 3.3 h^{-1} \text{ Mpc}$, so that peculiar motions account for less than 3% for structures larger than $100 h^{-1} \text{ Mpc}$. Thus, VLSS follow the Hubble expansion to good precision, or, in other words, very large scale structures should be comoving standard rulers.

3 Is their a specific scale for very large scale structures?

Since the report [2] of a redshift periodicity of structures on the scale of $130 h^{-1} \text{ Mpc} = 2 \pi/(0.048 h \text{ Mpc}^{-1})$, the existence of a preferred scale for very large scale structures, has been a matter of debate. As seen in Table 1, whereas many authors find sig-

| Ref. | Year | Survey | Objects | Number | Peak  | Dip   | Notes |
|------|------|--------|---------|--------|-------|-------|-------|
| 11   | 1997 | ACO    | clusters| 869    | 0.05  |       |       |
| 12   | 1998 | APM    | clusters| 364    | 0.08  |       |       |
| 13   | 2001 | ACO    | clusters| 637    | 0.04  |       |       |
| 14   | 2001 | REFLEX | clusters| 452    |       |       |       |
| 15   | 2001 | XBACS  | clusters| 242    | 0.035 |       |       |
| 16   | 2001 | BCS    | clusters| 301    | 0.08  |       |       |
| 17   | 1996 | LCRS   | galaxies| 24000  |       |       |       |
| 18   | 2000 | PSCz   | galaxies| 12400  | 0.028 | 0.036 | 1     |
| 19   | 2001 | 2dF    | galaxies| 100000 | 0.1   | 2     |       |
| 20   | 2002 | 2dF    | galaxies| 100000 | 0.05  | 0.1   | 3     |
| 21   | 2002 | 2dF    | quasars | 10000  | 0.069 |       |       |

Notes: 1) marginal peak and dip; 2) not deconvolved for survey geometry; 3) $(\Omega_m, \Omega_\Lambda) = (0.2, 0.8)$

significant peaks and dips in $P(k)$, measured from large surveys, they do not agree on their positions. In what follows, we will assume that there is a feature (peak or dip) in $P(k)$, which should lead to a quasi-periodic signal in the space distribution that is essentially frozen in comoving space.

4 The comoving standard ruler applied to quasars

After previous attempts [14, 15] on a low spectral resolution survey of quasars [8], we have analyzed the 2dF quasar sample, called 2QZ-10k [3], publicly made available in the Spring of 2001. After discarding poorly sampled regions (where the 

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1 We adopt, as the observers, the high definition of $P(k)$ ($(2\pi)^3$ higher than the low one).
survey completeness was less than 80%), leaving us with 2378 quasars, we computed the spatial two-point correlation function of the quasars in 3 redshift bins \( z = [0.6, 1.1], [1.1, 1.6], [1.6, 2.1] \), looking for features at the same comoving separations. The correlation functions were estimated as \( \xi(r) = \frac{DD - 2DR/n + RR/n^2}{RR/n^2} \), where \( DD, DR \) and \( RR \) indicate the number of data-data, data-random, and random-random quasar pairs respectively. We avoided redshift selection effects (emission lines will be visible in some intervals of redshift), by constructing our random catalogs with random angular positions, but redshifts obtained by scrambling the distribution in the dataset. The correlation functions were smoothed with a \( 15 \, h^{-1} \text{Mpc} \) gaussian.

We then repeated the exercise for \( 21 \times 21 \) pairs of \( (\Omega_m, \Omega_\Lambda) \), since the separation of two quasars depends on their angular separation and their two redshifts in a non-trivial function of \( \Omega_m \) and \( \Omega_\Lambda \).

Only in the region \( \Omega_\Lambda = 1.4 \Omega + 0.15 \pm 0.35 \) did we obtain strong peaks in the correlation functions. Figure 1 illustrates the subregion — the vertical ellipse centered on \( \Omega_m = 0.25 \pm 0.15 \) and \( \Omega_\Lambda = 0.65 \pm 0.35 \) (95% confidence) — where the peaks (at separation \( r = 244 \, h^{-1} \text{Mpc} \)) in the correlation function are at the same comoving separation in the three redshift bins. This appears to be the strongest joint constraint on \( \Omega_m \) and \( \Omega_\Lambda \) from a single survey.

Figure 1: left: \( \Omega_m \) and \( \Omega_\Lambda \) pairs for significant comoving peaks in the correlation function of 2QZ-10k quasars. right: Same for \( \Omega_m \) and \( w_Q \) (quintessence) pairs, assuming a flat Universe. From [16].

Figure 1 also displays the constraints on quintessence for the flat case \( w_Q = -1 \) in the standard model), and we find \( w_Q < -0.35 \) (95% confidence).

As a caveat, we have computed the expected correlation function from the power spectrum of \( \xi \), which we have padded with a CMBFAST calculation with \( (\Omega_m, \Omega_\Lambda, \Omega_b, h, \sigma_8) = (0.3, 0.7, 0.1, 0.6, 0.9) \) that fits well their \( P(k) \), using the relation

\[
\xi(r) = \frac{1}{2\pi^2} \int_0^\infty k^2 P(k) \frac{\sin(kr)}{kr} dk.
\]
We find oscillations in the $15\, h^{-1}\text{Mpc}$ gaussian smoothed correlation function that are 25 times smaller than found by [16]. We check this by considering a feature in $P(k)$ at wavenumber $k_0$ that has amplitude $L^3$ and width $\Delta$ decades in log $k$. If $\Delta \ll 1$, Eq. (2) yields $\xi \simeq \ln 10/(2\pi^2) (k_0 L)^3 \sin(k_0 r)/(k_0 r)$. If $\xi(r) \propto \sin(k_0 r)/(k_0 r)$ has a secondary maximum at $k_0 r_0 = 5\pi/2$, then $L^3 \Delta = 8 \xi(r_0) r_0^3/(25 \ln 10)$. For $r_0 = 244\, h^{-1}\text{Mpc}$ and $\xi(r_0) \simeq 0.03$ [16], we need $L^3 \Delta \simeq 6 \times 10^4 \, h^{-3}\text{Mpc}^3 = 1.5 P(k_0)$. So if the spike is, say, one-tenth of a decade wide, we need to locally boost $P(k)$ by a factor 15, whereas the measured peak [7] is only a factor 2 above the interpolated $P(k)$.

It seems clear that there is an inconsistency between these two analyses, and we are presently redoing our analysis of $\xi(r)$ from 2QZ-10k to resolve this question. Whether $\xi(r)$ or $P(k)$ is the better tool for detecting comoving standard rulers across distinct redshift intervals remains an open question.

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