A brief (personal) history of cosmology in Fourier space

John Peacock

Valencia, June 28 2006
Menu

- Selective history
- Where we are
- Outlook
1984: the quasar redshift cutoff

The high-redshift evolution of radio galaxies and quasars

J. A. Peacock Royal Observatory, Blackford Hill, Edinburgh EH9 3HJ

Accepted 1985 July 4. Received 1985 July 3; in original form 1985 April 24

Summary. This paper presents a new investigation into the evolution with cosmological epoch of the luminosity function for extragalactic radio sources. The free-form technique of Peacock & Gull has been applied to an increased data base of complete samples and number counts, with improved statistical methods, resulting in an important reduction of the uncertainties in the derived luminosity functions.

For the class of compact flat-spectrum sources, the present data require a redshift cut-off, with the luminosity function ceasing to evolve at $z=2$ and being reduced at $z=4$ by a factor of $\geq 3$ from its peak value.
Press & Schechter (1974) ... observe that if the initial density ... is a Gaussian process, then ... they assume that the positive (overdense) half of this Gaussian distribution is the frequency distribution of initial density contrasts in protoclusters ... It is doubtful that this is a good approximation, however ... one would prefer instead of the distribution of $M(x_0)$ for randomly placed $x_0$, the distribution of $M(x_0)$ for $x_0$ placed at local maxima of the function $M(x_0)$ (Jones 1976).
The origin of galaxies: A review of recent theoretical developments and their confrontation with observation

Bernard J. T. Jones

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and Institute of Astronomy, Madingley Road, Cambridge, CB3 0HA, England

An interesting possibility in this theory is of computing the luminosity function or the mass spectrum of objects that condense out of the universe. This has been attempted by Balko (1971) and by Press and Schecter (1974), but although the results seem fairly impressive, the problem is fraught with difficulties. In both these papers an attempt is made to compute the probability that an object of mass $M$ will condense from the universe. However, in both papers it is considered sufficient that $\delta \rho/\rho$ should reach the value unity for an inhomogeneity to be distinguished as a distinct object. The trouble with this simple view is that some condensations of mass $M$ may end up buried in larger condensations and therefore not be distinguished at the present day as individual objects. Thus instead of simply computing the probability that a given volume $V$ contains a mass whose fractional deviation from the ensemble average is $\delta M/M$, one ought to compute this probability subject to the condition that a slightly larger volume contains a mass whose fractional deviation from the ensemble average is less than $\delta M/M$. This of course complicates the problem enormously.

Actually points out the ‘cloud-in-cloud’ problem for Press-Schechter
Initially used FFT on
\[ \delta = \sum \delta_k e^{ik \cdot x} \]
+ central limit on random phases to make Gaussian realizations

Narrower range of density values (& hence collapse redshifts) than for random points, depending on power spectrum
Alternatives to the Press–Schechter cosmological mass function

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Accepted 1989 August 30. Received 1989 August 30; in original form 1989 July 24


⇒ PS halo mass function too sharply peaked

(cf. local random walk model)
Power spectra of radio galaxies


The Clustering of Radio Sources—I
The Theory of Power-Spectrum Analysis

Adrian Webster*
Mullard Radio Astronomy Observatory, Cavendish Laboratory, Cambridge
(Received 1975 October 24)

Summary
The theory of power-spectrum analysis of the clustering of points is described and developed as a sensitive and flexible test for the possible weak clustering of extragalactic sources.

Large-area angular distribution probes Gpc scales.

Test $P(k)$ against Poisson
⇒ homogeneous to few % for Gpc boxes

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Statistical Analysis of Catalogs of Extragalactic Objects. I. Theory*

P. J. E. Peebles
Joseph Henry Laboratories, Physics Department, Princeton University
(Received 1973 March 30)

Abstract
This paper is the first in a series on a systematic analysis of a number of catalogs of extragalactic objects. The method is based on the "analysis of power spectra," as elucidated by Tukey.
The large-scale clustering of radio galaxies

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Accepted 1991 July 8. Received 1991 June 27; in original form 1991 April 22

All-sky redshift survey of 329 objects to \( z = 0.1 \)

\[ \delta_k = N^{-1} \sum e^{ik \cdot x_i} - \text{FT}(\langle n \rangle) \]

\[ |\delta_k|^2 \approx 1/N \quad \text{estimates} \]

\[ P \ast |W_k|^2 \quad (\text{so prefer } \xi(r) \text{ for anisotropic survey geometry}) \]

Correct for integral constraint

Plot dimensionless \( P \):

\[ \Delta^2(k) = d\sigma^2/d \ln k \]

\[ = k^3 P(k) / 2 \pi^2 \]

Evidence for break at \( k \approx 0.02 \, h \, \text{Mpc}^{-1} \)
1990: APM $w(\theta)$

$$\Omega_m h \approx 0.2 \text{ (and argument for } \Lambda)$$

deprojected to $P(k)$ by Baugh & Efstathiou (1993)
Kaiser (1987): z-space distortions

\[ P_s = P_r (1 + \beta \mu^2)^2 \]
\[ \beta = \Omega_m^{0.6}/b \]
\[ \mu = k \cdot r / kr \]
Variety of data consistent with power spectrum shape \( \Omega_m h = 0.25 \) (allowing different bias factors) - not 0.15 because nonlinear evolution underestimated for very flat spectra.
Nonlinear evolution: HKLM91 – turned out to depend on $P(k)$

$\Omega_m h = 0.15$
The halo model

Neyman Scott & Shane (1953): random clump model: correlations arise from pairs in the same clump

\[ \rho \sim r^{-\alpha} \quad (r < R) \implies \xi \sim r^{-(2\alpha-3)} \]

obs:

\[ \xi \sim r^{-1.8} \implies \alpha = 2.4? \]

Application to CDM,
following Benson, Cole, Frenk, Baugh, Lacey 2000
Peacock & Smith 2000
Seljak 2000, 2002
Yang, van den Bosch, Mo et al. 2002a, 2002b, 2003
Power from haloes of different mass

PS++ mass function and NFW++ halo profile gives correct small-scale clustering from random haloes.

Add linear large-scale power for complete model.
Origin of power-law spectrum

Weight mass in haloes as $M^{-\alpha}$ for $M > M_{\text{min}}$:

$\alpha = 0.5$ and $M_{\text{min}} = 10^{12}$ works

Measure linear power for $k < 0.2$
Prediction matches correlation data

Zehavi et al.  
astro-ph/0301280

Luminous SDSS galaxies need weight $M^{-0.11}$ for $M > M_{\text{min}} = 10^{13.6}$
The 2dF Galaxy Redshift Survey

221,000 redshifts to B<19.45 (median z = 0.11)

250 nights AAT 4m time 1997-2002

public data: www.mso.anu.edu.au/2dFGRS
2dFGRS cone diagram: 4-degree wedge
$\Lambda$CDM predictions for the linear mass $P(k)$

$$\delta(x) = \frac{1}{(2\pi)^3} \int \delta(k) e^{i k \cdot x} \, dk$$

$$\langle \delta(k_1) \delta(k_2) \rangle = \delta^D(k_1 - k_2) P(k) \quad \Delta^2(k) = \frac{k^3}{2\pi^2} P(k)$$

- Varying the matter density times the Hubble constant
- Varying the inflation model
- Varying the baryon fraction
The final 2dFGRS Power Spectrum

Cole et al. 2005

Ω_m h = 0.168 ± 0.016

Ω_b/Ω_m = 0.185 ± 0.046
The eigenmode approach
(Vogeley & Szalay, Tegmark, Taylor & Heavens, Hamilton, late-90s)

Expand data vector \( d_i = \sum a_j \psi_{ij}(x) \), where modes are

**Orthonormal:** \( \psi_{ij} \cdot \psi_{jk} = \delta_{ik} \)

**Uncorrelated:** \( < a_i a_j > = 0 \)

Optimal basis \( \Rightarrow \) data compression and rapid likelihood,
thus fit sampled \( P(k) \) values as parameters

+ : Undoes mask convolution and z-space effects

− : Much more complicated to code and debug

− : Much slower to test on mock data
2dFGRS-SDSS comparison

Tegmark et al. vs Cole et al.

WMAP
CMB data evolution

Not quite angular power per ln(scale)

Flat $\Omega_m = 0.3$ (vacuum dominated)
Open $\Omega_m = 0.3$ (no vacuum)
Overall constraints:

Note in particular rejection of $n=1$
<table>
<thead>
<tr>
<th>Parameter</th>
<th>WMAP Only</th>
<th>WMAP + CBI + VSA</th>
<th>WMAP + ACBAR + BOOMERanG</th>
<th>WMAP + 2dFGRS</th>
</tr>
</thead>
<tbody>
<tr>
<td>$100\Omega_b h^2$</td>
<td>$2.233^{+0.072}_{-0.091}$</td>
<td>$2.203^{+0.072}_{-0.090}$</td>
<td>$2.228^{+0.066}_{-0.082}$</td>
<td>$2.223^{+0.066}_{-0.083}$</td>
</tr>
<tr>
<td>$\Omega_m h^2$</td>
<td>$0.126^{+0.0073}_{-0.0128}$</td>
<td>$0.1238^{+0.0066}_{-0.0118}$</td>
<td>$0.1271^{+0.0070}_{-0.0128}$</td>
<td>$0.1262^{+0.0050}_{-0.0103}$</td>
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<tr>
<td>$h$</td>
<td>$0.734^{+0.028}_{-0.028}$</td>
<td>$0.738^{+0.028}_{-0.037}$</td>
<td>$0.733^{+0.030}_{-0.038}$</td>
<td>$0.732^{+0.018}_{-0.025}$</td>
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<tr>
<td>$A$</td>
<td>$0.801^{+0.043}_{-0.054}$</td>
<td>$0.798^{+0.047}_{-0.057}$</td>
<td>$0.801^{+0.048}_{-0.056}$</td>
<td>$0.799^{+0.042}_{-0.051}$</td>
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<tr>
<td>$\tau$</td>
<td>$0.088^{+0.028}_{-0.034}$</td>
<td>$0.084^{+0.031}_{-0.038}$</td>
<td>$0.084^{+0.027}_{-0.034}$</td>
<td>$0.083^{+0.027}_{-0.031}$</td>
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<tr>
<td>$n_s$</td>
<td>$0.951^{+0.015}_{-0.019}$</td>
<td>$0.945^{+0.015}_{-0.019}$</td>
<td>$0.949^{+0.015}_{-0.019}$</td>
<td>$0.948^{+0.014}_{-0.018}$</td>
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<tr>
<td>$\sigma_8$</td>
<td>$0.744^{+0.050}_{-0.060}$</td>
<td>$0.722^{+0.044}_{-0.056}$</td>
<td>$0.742^{+0.045}_{-0.057}$</td>
<td>$0.737^{+0.033}_{-0.045}$</td>
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<tr>
<td>$\Omega_m$</td>
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<td>$0.229^{+0.026}_{-0.042}$</td>
<td>$0.239^{+0.025}_{-0.046}$</td>
<td>$0.236^{+0.016}_{-0.029}$</td>
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<table>
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<tr>
<th>Parameter</th>
<th>WMAP+ SDSS</th>
<th>WMAP+ LRG</th>
<th>WMAP+ SNLS</th>
<th>WMAP+ SN Gold</th>
<th>WMAP+ CFHTLS</th>
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<tr>
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<td>$2.242^{+0.062}_{-0.084}$</td>
<td>$2.233^{+0.069}_{-0.088}$</td>
<td>$2.227^{+0.065}_{-0.082}$</td>
<td>$2.247^{+0.061}_{-0.082}$</td>
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<tr>
<td>$\Omega_m h^2$</td>
<td>$0.1329^{+0.0057}_{-0.0109}$</td>
<td>$0.1337^{+0.0047}_{-0.0098}$</td>
<td>$0.1295^{+0.0055}_{-0.0106}$</td>
<td>$0.1349^{+0.0054}_{-0.0106}$</td>
<td>$0.1410^{+0.0042}_{-0.0094}$</td>
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<tr>
<td>$h$</td>
<td>$0.709^{+0.024}_{-0.032}$</td>
<td>$0.709^{+0.016}_{-0.026}$</td>
<td>$0.723^{+0.021}_{-0.030}$</td>
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<td>$A$</td>
<td>$0.813^{+0.042}_{-0.052}$</td>
<td>$0.816^{+0.042}_{-0.049}$</td>
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<td>$0.852^{+0.036}_{-0.047}$</td>
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<tr>
<td>$\tau$</td>
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<td>$0.082^{+0.028}_{-0.033}$</td>
<td>$0.085^{+0.028}_{-0.032}$</td>
<td>$0.079^{+0.028}_{-0.034}$</td>
<td>$0.088^{+0.021}_{-0.031}$</td>
</tr>
<tr>
<td>$n_s$</td>
<td>$0.948^{+0.015}_{-0.018}$</td>
<td>$0.951^{+0.014}_{-0.019}$</td>
<td>$0.950^{+0.015}_{-0.019}$</td>
<td>$0.946^{+0.015}_{-0.019}$</td>
<td>$0.950^{+0.015}_{-0.019}$</td>
</tr>
<tr>
<td>$\sigma_8$</td>
<td>$0.772^{+0.036}_{-0.048}$</td>
<td>$0.781^{+0.032}_{-0.045}$</td>
<td>$0.758^{+0.038}_{-0.052}$</td>
<td>$0.784^{+0.035}_{-0.049}$</td>
<td>$0.826^{+0.023}_{-0.035}$</td>
</tr>
<tr>
<td>$\Omega_m$</td>
<td>$0.266^{+0.025}_{-0.040}$</td>
<td>$0.267^{+0.017}_{0.020}$</td>
<td>$0.249^{+0.023}_{-0.034}$</td>
<td>$0.276^{+0.022}_{-0.036}$</td>
<td>$0.301^{+0.018}_{-0.031}$</td>
</tr>
</tbody>
</table>
Does tilt alone verify inflation?

Harrison-Zeldovich-Peebles: mustn’t have a characteristic scale

\[ \Rightarrow \Delta_{\Phi}^2(k) \equiv \delta_{H}^2(k) \propto k^{n-1} = \text{const} \]

But there is always a characteristic length: \( L_{\text{planck}} \)

\[ \delta_{H}(L) = \epsilon \ln(L/L_{\text{Planck}}) \simeq 10^{-5} \]
\[ \Rightarrow 1 - n = 2/\ln(L/L_{\text{Planck}}) \simeq 0.03 \]

If tilt is generic, need tensors too for a test of inflation
Inflation models

mass-like potential $V(\phi) \propto \phi^2$ is now the standard model
The big puzzle: what is the vacuum energy?

(1) Zero-point energy

\[ E = \sum \text{modes} \frac{\hbar \omega}{2} \]

⇒ expect \( \rho_{\text{vac}} \sim E_{\text{max}}^4 \) (natural units: \( c=\hbar=1 \))

But empirically \( E_{\text{max}} = 2.4 \text{ meV} \) - not a real cutoff

(2) Dynamical ‘Dark Energy’

- Empirical \( w = P/\rho \ c^2 \); fit \( w(a) = w_0 + w_a (1-a) \)

- ‘Quintessence’: use inflationary technology of \( w<0 \) from scalar fields
Measuring the vacuum

Vacuum affects $H(z)$:

$$H^2(z) = H_0^2 \left[ \Omega_m (1+z)^3 + \Omega_r (1+z)^4 + \Omega_v (1+z)^{3(1+w)} \right]$$

matter radiation vacuum

Alters $D(z)$ via $r = \int c \, dz/H$

And growth via $2H \, d\delta/dt$ term in growth equation

Both effects are

1. Small (need $D$ to 1% for $w$ to $\pm 0.05$)
2. Degenerate with changes in $\Omega_m$

Redshift surveys of $\sim 10^6$ galaxies over $\sim 1000$ deg$^2$ can measure $w$ to 3-5% but systematics are challenging

Now: AAO ($2dF++$) 2012: WFMOS
P(k) as a standard ruler

(1) Matter-radiation horizon:
\[ 123 \left( \Omega_m h^2 / 0.13 \right)^{-1} \text{ Mpc} \]

(2) Acoustic horizon at last scattering:
\[ 147 \left( \Omega_m h^2 / 0.13 \right)^{-0.25} \left( \Omega_b h^2 / 0.024 \right)^{-0.08} \text{ Mpc} \]

Acoustic horizon can be seen in CMB and baryon wiggles:
Use to probe distance-z relation

\[
D(z) = \frac{c}{H_0} \int_0^z \frac{dz}{\left[ (1-\Omega_m)(1+z)^{3+3w} + \Omega_m(1+z)^3 \right]^{1/2}}
\]

can measure w for vacuum \((P/\rho \ c^2)\)
The vacuum: present knowledge

Combined:

\[ w = -0.926 \pm 0.075 \]

So far, constraint comes from overall break in \( P(k) \)
Wiggles in the 2dFGRS Power Spectrum

Cole et al. 2005
Wiggles in SDSS LRG correlations

Eisenstein et al. astro-ph/0501171:
46,748 Luminous Red Galaxies $0.16 < z < 0.47$ ($<z> = 0.35$)

Compare Horizon in CMB:
$w = -0.80 \pm 0.18$ if flat
Origin of baryon features: real space

Eisenstein www
Origin of baryon ‘wiggles’

density

space

time
Origin of baryon ‘wiggles’

density

space

time
Origin of baryon ‘wiggles’

density

space

time
Origin of baryon ‘wiggles’

density

space

time
Origin of baryon ‘wiggles’

density

space

time
Origin of baryon ‘wiggles’

density

colors:
- black
- red

time

space
Origin of baryon ‘wiggles’

Baryons (+ photons) oscillate as standing waves.

Oscillations damp on small scales: switch off DM growth until matter domination.
Evolution of transfer functions

$z = 1000, 100, 0$

Wiggles in CDM arise after last scattering, and are in place only at $z=50$
Baryon wiggles as a ruler: w to few % accuracy

Blake/Glazebrook proposal:

\[ 2 \times 10^6 \text{ g's over } 600 \text{ deg}^2 \]

\[ 0.5 < z < 1.3 \]
S/N formula for P(k)

\[
\begin{align*}
\sigma |\ln P | & = \frac{2\pi}{(V k^2 \Delta k)^{1/2}} \left( \frac{1+nP}{nP} \right) \\
\end{align*}
\]

For \(nP << 1\), shot noise dominates

For fixed telescope time \(V \propto 1/n\), so \(nP=1\) is optimal

Typical \(P=2500\) \((h^{-1}\text{Mpc})^3\) \(\Rightarrow n_{\text{opt}} = 4 \times 10^{-4}\) \((h^{-1}\text{Mpc})^{-3}\)

Similar clustering for many high-z tracers

\[
\% \text{ error on } D(z) = (V / 5 \ h^{-3} \ \text{Gpc}^3)^{-1/2} \times (k_{\text{max}} / 0.2 \ h \ \text{Mpc}^{-1})^{-1/2}
\]

Can we go to higher \(k\) at high \(z\) (smaller nonlinearities)?

Feldman, Kaiser, JP, 1994
WFMOS

Proposed 2000-4000 Fibre spectrograph for 1.5-degree HyperSuprime field on Subaru 8m, in collaboration with Gemini. Data from 2012 if approved.

Targets: emission-line galaxies at z=1 and LBGs at z=3

- $0.7 < z < 1.3$: $1 \left( h^{-1} \text{Gpc} \right)^3 = 540 \text{ deg}^2$
- $2.5 < z < 3.5$: $1 \left( h^{-1} \text{Gpc} \right)^3 = 254 \text{ deg}^2$

- Thus 1% distance accuracy ($V=5$) needs 2000 or 1000 deg$^2$

- At optimal density, means 2,000,000 galaxies at $z=1$ and 600,000 at $z=3$
Flat: BAO at $z=1$ and $z=3$
Pivot redshifts

Assume \( w = w_0 + w_a(1-a) \)

If observe degeneracy \( w_0 = A + Bw_a \),

\[ \Rightarrow w = A + (B+1-a)w_a \]

\[ \Rightarrow z_{\text{pivot}} = \frac{1}{1+B} - 1 \]

<table>
<thead>
<tr>
<th>Method</th>
<th>( z_{\text{pivot}} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>BAO ( z=1 )</td>
<td>0.54</td>
</tr>
<tr>
<td>BAO ( z=1+3 )</td>
<td>0.85</td>
</tr>
</tbody>
</table>

Difficult to get much baseline

WFMOS could measure \( w_{\text{pivot}} \) to \( \pm 0.05 \) and \( w_a \) to \( \pm 0.15 \)
Is this accurate enough to be interesting? May need much larger numbers (e.g. ADEPT)

– and in any case, can we measure the effect?
Galaxy clustering in the Millennium Simulation

Dark matter

Galaxies

The galaxy content of a $10^{14} \, M_\odot$ halo
Power spectrum from MS divided by a baryon-free $\Lambda$CDM spectrum

Galaxy nonlinearities higher at $z=3$ than $z=1$
Scale shifts at $z=1$  (Stuart Lynn)

Need to predict this to $<< 1\%$
Conclusions from galaxy P(k)

- Only weak acoustic oscillations. Must have collisionless component
- CDM models work, with sensible baryon fraction
- Low density $\Omega_m \sim 0.25$ when CMB added
- BAO signature will be one of the key DE probes
  - But still much to do in controlling systematics