The Future Utilisation of Schmidt Telescopes
ASP Conference Series, Vol. 84, 1995
J. M. Chapman, R. D. Cannon, S. J. Harrison and B. Hidayat (eds)

Cosmology with Stacked Schmidt Plates

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Abstract. Digital stacking of Schmidt Plates greatly increases the depth of the data allowing detection of galaxies at $\bar{z} \sim 1$. We can probe the angular correlations of galaxy and cluster positions over scales of $\sim 500h^{-1}$Mpc. Radial distance information can be obtained by identifying radio galaxies in the field and using their "standard candle" properties. A search for cosmic string effects, beginning with the stacked dataset, has now been extended to ~ 100 equatorial J-plates.

1. Introduction

A current project at the ROE is the co-addition or "stacking" of Schmidt plates to generate star and galaxy catalogues with very faint limiting magnitudes. For many southern sky field/filter combinations there exist several plates which can be digitised by the COSMOS plate measuring machine, co-added then subjected to the usual image analysis software to generate an object file. Star/galaxy discrimination is possible, at least for the brighter images. For field 287 we have combined 66 J-plates yielding data that are complete down to $B_J \sim 25$ (Fig. 1). This stack, therefore, probes depths traditionally associated with CCD data, whilst preserving the large area coverage associated with photographic surveys. Hawkins will be discussing some of the technical details and applications at this symposium. Our aim here is to summarise the implications of the data for cosmology, namely large-scale structure statistics from the galaxy distribution. We will then go on to outline a programme to search for cosmic strings on both the stacked datasets and ~ 100 high galactic latitude, equatorial J plates.

2. Angular Correlation Function

The two-point angular correlation function $w(\theta)$ is defined by the equation

$$\delta P = \overline{N}^2(1 + w(\theta))\delta\Omega_1\delta\Omega_2 \tag{1}$$

with δP the probability of finding a galaxy in each of the solid angle elements $\delta\Omega_{1,2}$ at separation θ, and $\overline{N}$ the mean surface density of galaxies. This function and its higher-point counterparts provide a relatively simple means of quantifying clustering in the 2D galaxy distribution to compare with theory and data from other surveys. At moderate depths of $m_B \leq 20$ and at small angular scales, $w(\theta)$ has been found to be well described by:

$$w(\theta) \propto \theta^{-0.8} \tag{2}$$

One problem with $w(\theta)$ as a statistic is that projection of the 3D galaxy distribution on to the 2D plane dilutes the amplitude of the clustering pattern. The deeper the catalogue, the greater the dilution. In addition, at fainter magnitudes (and hence greater distances) the same physical size subtends a smaller angle. These two effects give rise to the (non-evolving) scaling relation

$$w(\theta) = \frac{1}{D} W(\theta D) \tag{3}$$

with D, the effective depth of the data, dependent on the limiting magnitude: $D \propto 10^{0.2 m_{lim}}$.

The deepest large-scale optical survey to date, the APM galaxy survey (Maddox et al. 1990), took $\sim 2 \times 10^6$ galaxies at $B_J \leq 20.5$ with an effective depth $D \simeq 600h^{-1}$Mpc and deduced the following properties:

(a) $w(\theta)$ departs from a power law at $\theta \sim 2°$, i.e. a scale of $\sim 20h^{-1}Mpc$;

(b) the scaling law is obeyed down to $B_J = 20.5$;

(c) there is excessive large scale structure compared to the standard CDM model.

D for $B_J \leq 25$ is about 10 times greater than for the APM survey so applying the scaling law to the APM data we can estimate that $w(15'') \simeq 0.03$ for the stack, with a power law break at around 0.2°. Measuring $w(\theta)$ is a matter of taking each catalogued galaxy in turn and finding its angular separation from all the other galaxies in the field, histogramming the data into bins of width $\Delta\theta$ and then comparing this distribution with that of a set of uncorrelated random points over the same area. Regions around bright stars and galaxies are excluded from both the real and random catalogues to ensure the same selection effects. We employ the estimator

$$w(\theta) = \frac{N_{dd}(\theta)}{N_{dr}(\theta)} \frac{2n_r}{n_d} - 1 \tag{4}$$

with N_{dd} and N_{dr} the number of distinct data-data and data-random pairs, and n_d and n_r the total number of data and random points respectively. Data-random pairing is considered to be more robust than random-random pairing in accounting for edge effects due to clustering near the field boundary.

A "first guess" analysis of $w(\theta)$ for the stack suggests $w(15'') \simeq 0.03$ in line with the APM prediction. This is very much a rough estimate based on a small

($\sim 1°$) portion of the plate (Fig. 2). In addition to suffering Poissonian noise of order $N_{dd}^{-1/2}$ our estimator is sensitive to assumptions about the mean density as derived direct from the field. All the data ($\sim 10^6$ galaxies) and a careful statistical analysis will be required to accurately fix such a low amplitude $w(\theta)$.

A recent analysis of the implications of deep angular correlation amplitude measurements is given by Yoshii et al., (1993; YBT). With reference to equation (3) it is not at all clear that $w(\theta)$ *should* be non-evolving, and at very high redshifts ($z > 1$) it will certainly not be. Small area CCD measurements suggest that at $VR \leq 23.5$[1] no depth dependent trends become apparent (Couch et al., 1993). Efstathiou et al. (1991) find very low values for $w(30'')$ at $B_J \sim 26$ which they interpret as either

(i) relating to a new population of weakly clustered faint galaxies at $B_J \sim 26$ which are very faint at the present epoch

or

(ii) an indication that clustering evolves far more rapidly than permitted by currently fashionable cosmological models.

YBT question the analysis of Efstathiou et al. suggesting that their parameterisation of the redshift dependence, $(1+z)^{-\alpha}$ with α a positive constant, is too crude. Instead YBT conclude that the clustering amplitude has a complicated dependence on the model universes, which the measurement is too imprecise to discriminate between. A careful extraction of $w(\theta)$ from the stacked data should help to constrain these important values more accurately.

3. Three Dimensional Clustering Statistics

The two-point correlation function can be analytically "de-projected" by the use of integral transform methods to yield an estimate of the corresponding 3D correlation function $\xi(r)$. Such calculations suffer according to the extent to which projection has degraded the original signal and rely heavily on a good estimate for the galaxy luminosity function.

In practice, therefore, it is extremely useful to have some estimate of radial distances in the sample. For relatively shallow surveys, redshifts can be obtained spectroscopically for sufficiently bright galaxies and compared with the Hubble redshift-distance relation. The data can, however, be distorted by the "fingers of God" effect in which the peculiar velocities of galaxies in virialized clusters contribute to the redshift and smear out the inferred distribution of galaxies that are actually at the same distance.

Most of the galaxies in our stack are far too faint for spectroscopic investigation. We propose instead to derive relatively rough redshift estimations by identifying radio sources in field 287 and using the "standard candle" properties

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[1] Couch et al. define the VR band as effectively the average of V and R magnitudes (i.e. $VR = [V + R]/2$)

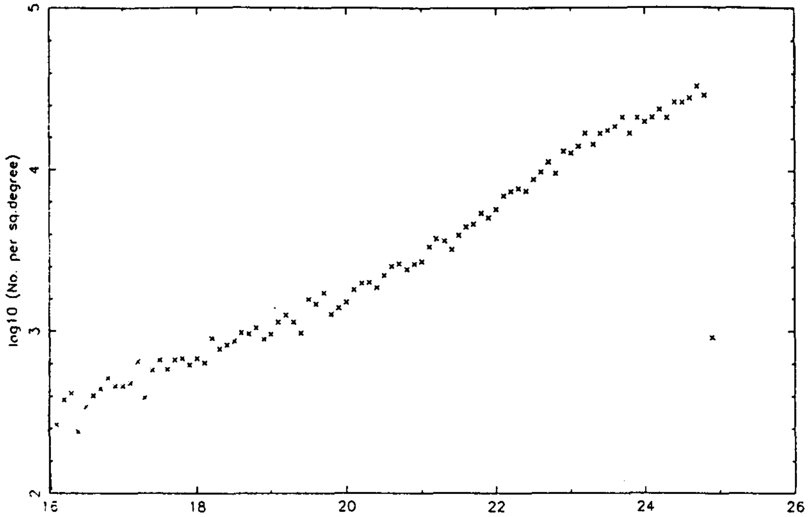

Figure 1. Differential star/galaxy counts in number per square degree per magnitude for the 66 plate J-stack (field 287). Comparison with other deep survey data (e.g. Koo & Kron 1992) suggests completeness down to $B_J = 24.75$

of their optical host galaxies. Such information can be obtained in two ways. Firstly there is a well defined K magnitude-redshift relation for radio galaxies (Lilly & Longair 1984). Secondly, with two deep stacks in different wavebands (i.e. J and R) we can derive colours for the optical counterparts of the radio galaxies. J and R sample a steeply falling part of the spectral emission of these galaxies. Any redshifting of luminosity into or out of these filters will manifest itself as a dependence of colour on distance (e.g. Dunlop & Peacock 1993).

We plan to use the Molonglo Radio Survey which claims a positional accuracy of $\sim$ 3" for detected sources within some reasonable bracket of radio power (Hindmarsh 1991). Even at the number densities on the stack this accuracy will allow us to match radio galaxies to their corresponding optical images fairly unambiguously. We can use the distance information to radially "slice up" the stack and so extract the 3D two-point correlation function with greater confidence.

4. Cosmic Strings

Cosmic strings are a class of "topological defect" which arise in some grand unified theories of the very early universe. They form $\sim 10^{-35}$s after the Big Bang during a symmetry breaking phase transition as the universe falls below some critical temperature. The general relativistic properties of strings have been investigated by Vilenkin(1986) and Gott(1985). They find that the exterior

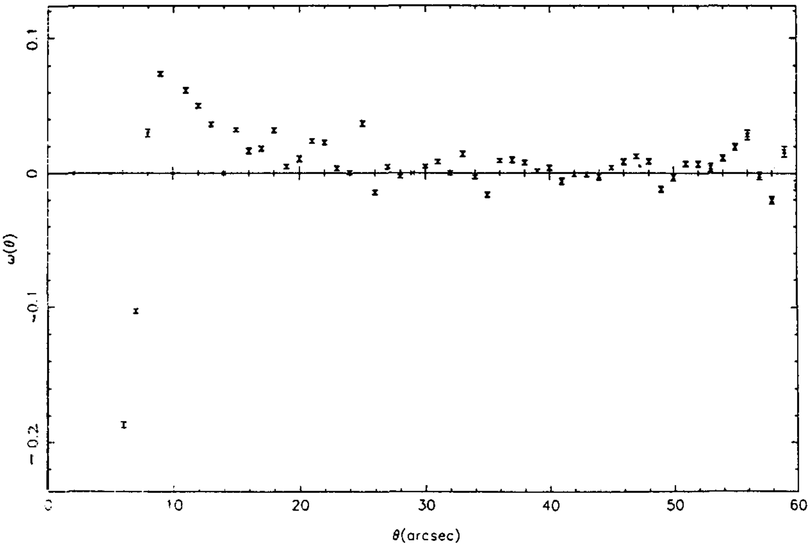

Figure 2. Angular correlation function for a ~ $1\mathrm{deg}^2$ region of the J-stack. Note the apparent anti-correlation below ~ 6", this reflects the deblending limitations of COSMOS.

gravitational field of an infinite straight string corresponds to a "conical space" This is the same as "flat" Minkowski spacetime except for an effective *angle deficit* of $8\pi G\mu/c^2$ with μ the mass-per-unit-length of the string.

As a result, particles moving either side of the string on initially parallel trajectories would subseqently *converge* and form shock regions in wakes behind the string (Fig. 3). Similarly light can be *lensed* by the string. If a string lay in front of an observable galaxy within ~ $8\pi G\mu/c^2$ of the line of sight then lensing effects would give rise to two images of the galaxy with angular separation

$$\Delta\theta = \frac{8\pi G\mu}{c^2}\frac{z_g - z_s}{z_g} \tag{5}$$

The detection of a cosmic string would be of huge importance for cosmology and particle physics. The presence of strings would provide a mechanism for producing cosmological inhomogeneities relating to present large-scale structure in the universe (Albrecht and Stebbins 1992). Furthermore a determination of the mass-per-unit-length would allow a direct measurement of the grand unification scale. Strings could reveal themselves by producing discontinuous jumps in the intensity of the microwave background radiation. An analysis of the COBE results (Bouchet et al. 1988; Bennet et al. 1992) shows the temperature variations to be consistent with the string model if $\mu = 1.5 \pm 0.5 \times 10^{-6} c^2/G$. This value is in good agreement with the size required for structure formation and also with

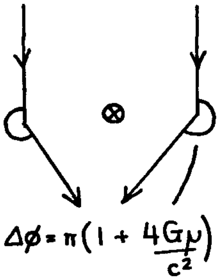

Figure 3(a)

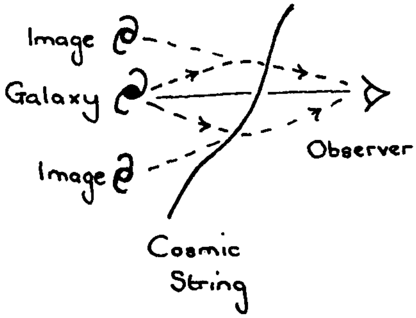

Figure 3(b)

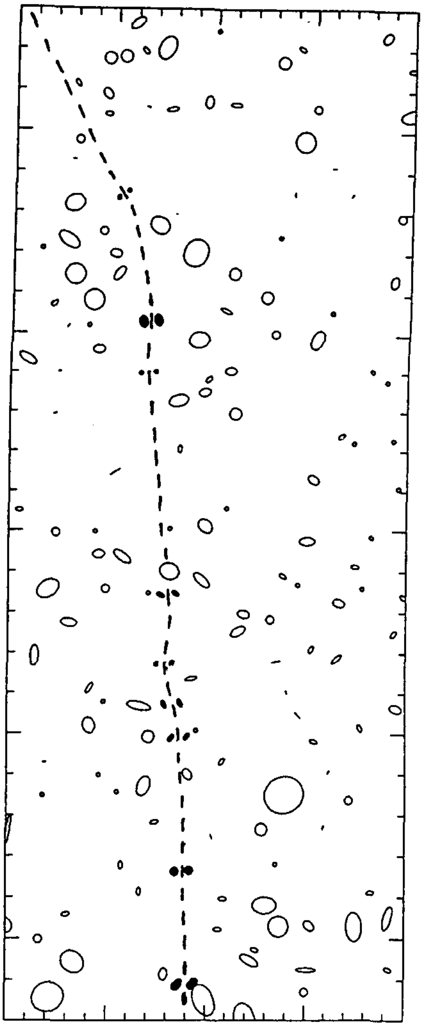

Figure 4

Figure 3. The lensing behaviour of cosmic strings. Light moving either side of the string has its path *bent* by the gravitational field (a). This can give rise to double galaxiy images (b).

Figure 4. Simulation of Schmidt field containing a cosmic string. Lensed galaxy pairs are in black. The dashed line shows the locus of the string.

the energy scale of grand unification (i.e. symmetry restoration) of strong, weak and electromagnetic interactions, $\sim 10^{16} GeV$.

We propose to search for cosmic strings via the gravitational lensing effect discussed above. The Bennet et al. value for μ gives us a maximum lensing angle of ~ 8". The search method is based on a scheme due to Hindmarsh (see references) in which strings are identified from deep survey plates by the presence of correlated lensed galaxy pairs. Of course at faint magnitudes we cannot easily distinguish lensed galaxies from distinct galaxy pairs less than 8" from each other. Instead we have to hope that the string gives us enough pairs along some locus to lift its "signal" above the random pairing "noise". Furthermore, 8" is close to the limit down to which the COSMOS deblending software proves reliable (Beard et al. 1990). We therefore have to include some of the more ellipsoidal images which *could* be unresolved pairs.

The search procedure works as follows. The COSMOS image analysis file of a J-plate or J-stack is obtained. A catalogue is produced of images of comparable magnitude which lie within 8" of each other and of single images of high ellipticity. The images are then sorted into angular bins according to orientation (we take a range of bin sizes from 5° to 180°). Each pair/ellipse is taken as the centre of an ~ 8" wide strip and a count is made of other objects in the same orientational bin which lie within the strip. Because of an aberration effect which arises from relativistic transverse motion of strings, the strips are allowed a full range of shear angles relative to the orientation of the current bin. Strips which contain a sufficienly high number of co-directional images are recorded as string candidates.

Tests on cosmic string simulations (Fig. 4) give us confidence in this search procedure out to $z_s \sim 0.15$. Hindmarsh suggests that at these redshifts an area of about $2000 \mathrm{deg}^2$ would need to be examined for a clear detection to result. We have taken ~ 50 fields thus far to produce a list of the best candidates over this part of the sky and we aim to analyse about 50 more. Our stacked dataset is worth about 5 J-plates in terms of depth coverage and the far greater image number density would yield more lensed pairs though with a corresponding increase in random close-pair noise. To further confirm or reject our candidates will require higher resolution CCD images of each object. A concrete detection would clearly be of great significance to science, although a failure would alse be important as it would strongly constrain the parameters of the string scenario.

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Discussion

McConnell: What is the minimum number of close pairs needed as evidence for a cosmic string? Upon what parameters does the probability depend?

McNally: For a single J-plate, the number of close pairs produced by a string at $z \sim 0.15$ is about 20 (taking the median redshift of galaxies on the plate to be ~ 0.2). An $8''$ wide strip picks up about 10 "random" close pairs across a typical plate. We take strips containing $\sim$ 15 or more aligned pairs as worthy of further investigation. The lensing probability depends on the mass per unit length of the cosmic string, the string redshift and the median galaxy redshift on the plate. The mass per unit length is constrained by the COBE measurements to be $\sim 1.5 \pm 0.5 \times 10^{-6} c^2/G$.

Gilmore: Reliable determination of the correlation function and its scaling is very sensitive to reliable star-galaxy separation. We were told that this is unreliable in your data. Would you care to comment?

McNally: Although at these faintnesses, the galaxy counts significantly exceed the star counts, discrimination between the two object types is still of importance. COSMOS proved fairly unsatisfactory at these leves as mentioned by Hawkins (these proceedings). However, this is an on-going project and the imminent arrival of SuperCOSMOS (with better image sampling) and the FOCAS software, with more subtle image analysis, should alleviate some of these problems.