TITLE
*ASP Conference Series, Vol. **VOLUME***, **YEAR OF PUBLICATION***
NAMES OF EDITORS

The Two Degree Field Galaxy Redshift Survey (2dFGRS): The Instrument, Data, and Science

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Abstract. The 2dFGRS contains over two hundred twenty thousand galaxy redshifts obtained with the two degree field fiber spectrograph facility at the prime focus of the 4 m Anglo-Australian Telescope. The photometric catalog, and all spectra are publicly available on-line, and as a CD-ROM/DVD-ROM set. The main cosmological results are: the measurements of the correlation function and of the power spectrum of the galaxy distribution, the determination of the mass density of the Universe, $\Omega_m = 0.29 \pm 0.05$, the determination of the baryon fraction through the effects of baryon-photon coupling, $\Omega_b/\Omega_m = 0.15 \pm 0.07$, a direct measurement of the absolute value of the bias parameter, $b = 1.0 \pm 0.1$, a limit on the neutrino mass, $m_\nu < 1.8$ eV, and by combining the 2dFGRS results with CMB anisotropy measurements, a determination of the value of the cosmological constant, $\lambda = 0.7 \pm 0.1$, and of the Hubble constant, $h = 0.72 \pm 0.07$. In addition, a wide range of results on the properties of the galaxy population have been obtained.

1. Introduction

The 2dF Galaxy Redshift Survey has obtained a quarter of a million spectra using the two degree field fiber spectrograph facility at the prime focus of the 4 m Anglo-Australian Telescope, located in Siding Spring Observatory, near Coonabarabran, New South Wales, Australia.

The source catalog is derived from Automatic Plate Measuring machine (APM) scans of UK Schmidt Telescope plates (Maddoox et al. 1990a, 1990b, 1990c). The Kodak IIIaJ plates and GG395 filter define a b_j magnitude that

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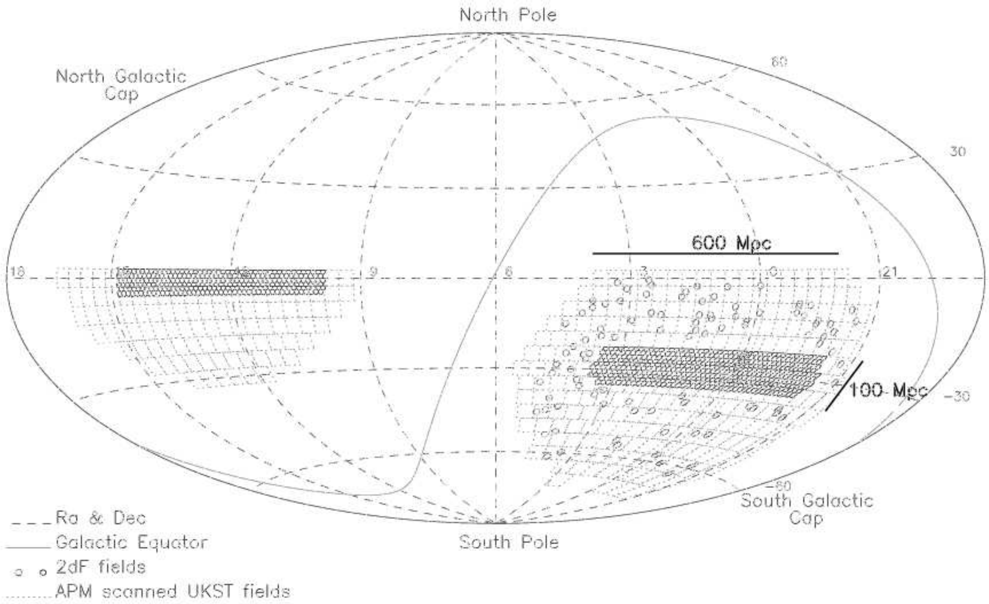

Figure 1. The 2dFGRS survey area. The small circles represent the individual 2° survey fields. The squares represent the scanned plates in the APM catalog.

is related to the Johnson-Cousins B magnitude by $b_j = B - 0.28(B - V)$. The limiting magnitude of the survey is an extinction corrected $b_j = 19.45$.

The area of the galaxy redshift survey covers two contiguous strips, and 100 random 2° fields spread uniformly over the 7000 deg^2 of the southern APM catalog, as shown in Figure 1. The $75° \times 7.5°$ strip along the celestial equator in the northern Galactic Hemisphere contains 70,000 target galaxies. The $75° \times 15°$ strip through the South Galactic Pole contains 140,000 target galaxies. The random fields in the southern Galactic Cap contain another 40,000 target galaxies. At the end of the survey (May 2002) 271,229 non-unique, 246,677 unique redshifts had been obtained. Of the unique redshifts, 14,049 are stars ($z < 0.002$), 180 are QSOs, and 221,283 are galaxies with good quality ($Q \geq 3$) spectra. The overall completeness is 93% in the 2° fields that were observed.

2. The 2dF Instrument

The Anglo-Australian Telescope is a 4 m class telescope with three top-ends that can be changed to provide an f/3.3 prime focus (3 correctors with fields of 60 arcmin, 25 arcmin, and 10 arcmin), an f/8 Ritchey-Chrétien Cassegrain secondary (30 arcmin field), and two f/15-f/36 Cassegrain-coudé secondaries that can be interchanged within the single top-end (small on axis fields).

A new top-end was constructed by the Anglo-Australian Observatory for their 2dF fiber spectrograph facility. The 2dF corrector consists of 5 elements. The first two elements are counter-rotating prismatic doublets 0.87 m and 0.84 m in diameter that act as an atmospheric dispersion compensator for zenith

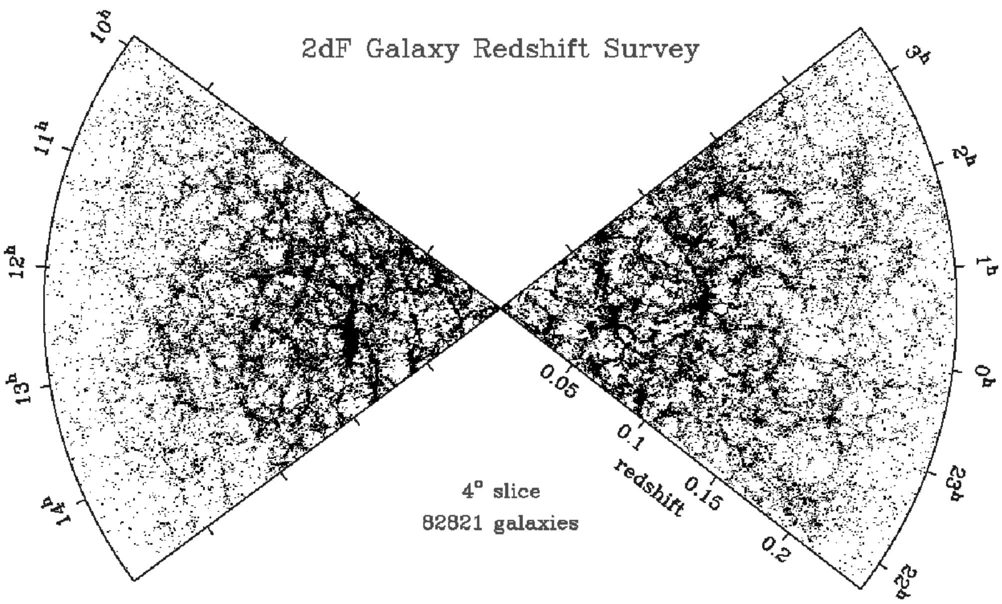

Figure 2. The distribution of galaxy redshifts in the northern and southern 2dFGRS strips, in a slice 4° thick in declination (Peacock 2002). The galaxy distribution has a frothy nature. All structures are significantly smaller than volume of the Universe surveyed.

distances of up to 67°. These doublets are followed by two single element lenses. This corrector lens system provides an f/3.5 corrected field that is 2.1 degrees in diameter, at a scale of 67 μm/arcsec.

There are two spectrographs mounted on the top-end ring. Each spectrograph records the spectra produced by 200 fibers, so that 400 spectra are obtained simultaneously. There are two interchangeable field plates, each with its own set of fibers, so that fibers can be positioned on one plate, while observing continues using the fibers on the other plate. The time needed to interchange the two plates and fiber sets under remote control is similar to the time required to slew the telescope to a new field.

The spectrographs use 150 mm beam, f/3.15 off-axis Maksutov collimators and f/1.0 (spectral), f/1.2 (spatial) modified Schmidt cameras with a CCD detector at the camera prime focus. The dispersion is 4.8 Å per pixel, and the spectra are separated on the detector by 5 pixels. Total system throughput is about 5 percent, including the atmosphere, telescope, corrector, fibers, grating, and spectrograph. The spectrum of a typical $B = 19$ galaxy has a signal/noise ratio of > 10 per pixel in less than one hour.

Each fiber is 8 m in length, 140 μm (2.1 arcsec) in diameter, and is held in the focal plane by a magnetic button positioned on a steel plate. The fibers run out across the focal plane under tension from retractors around the circumference of the field. A microprism on the end of each fiber bends the incident light through 90° into the fiber which lies parallel to the focal plane. The magnetic buttons are positioned in the focal plane by a gripper on an XY gantry above the focal plane. The XY gantry is moved by computer control of linear AC servo motors. Each axis has optical encoders with 1.25 μm resolution. In order to avoid any telescope shake, motions of the XY gantry are balanced by counter weights that move in the opposite direction. The fibers are back illuminated during positioning so that a CCD camera in the gripper can 'see' the fiber core and ensure that the final position of the fiber is correct. The RMS positioning precision is 20 μm (0.3 arcsec). Because fibers can cross on top of other fibers, a typical re-configuration of 400 fibers requires about 600 moves to untangle an old configuration and setup a new configuration. At 6 s per move, this takes about 1 hour.

Guiding during the exposure is done by a digital camera that views the light from four guide bundles. Each guide bundle has 7 fibers in a hexagonal arrangement around one central fiber.

A typical observing sequence consists of calibration exposures of a incandescent lamp and an emission line arc, followed by three integrations on the galaxy field. A pipeline data reduction system assigns wavelengths to the spectra, subtracts a weighted sky spectrum derived from a few fibers placed on blank sky, cross-correlates the galaxy spectrum with several templates, and displays the spectrum and best cross-correlation for the observer to assess. The spectrum is displayed with common galaxy emission and absorption lines marked on the display at the cross-correlation redshift, and the redshift is marked on the cross-correlation display. The observer may intervene to manually determine a redshift, or may simply assign a quality to the redshift. Every spectrum has been through the data reduction pipeline and been viewed and assessed before the start of the next night of observations.

The Anglo-Australian Observatory's 2dF facility is described in more detail by Lewis et al. (2002).

3. The 2dFGRS Database

The 2dFGRS database has two main parts: a collection of FITS files and an SQL query engine with HTML pages for submitting queries and displaying results.

There is one multi-extension FITS file for each target in the survey. The first extension contains a DSS image of the target, and APM photometric parameters in keywords. If one or more spectra were obtained, subsequent extensions contain the sky-subtracted, wavelength calibrated, spectrum. Parameters derived from the spectrum, such as the redshift, are in keywords in the extension containing the spectrum to which they apply. The spectrum is stored as a two dimensional array, with the spectrum in row 1, and the variance array, and sky spectrum in the other rows.

The SQL query engine allows the selection of targets by various criteria, such as magnitude, redshift, position on the sky, etc. Results can be returned as the FITS files, or as a text or HTML data table for the targets that meet the SQL query criteria. If the HTML table is requested, then the DSS image and the spectrum of each target in the table can be selected for display with the web browser.

Users can also search for survey targets around specified positions on the sky, and submit lists of objects to be matched with survey targets.

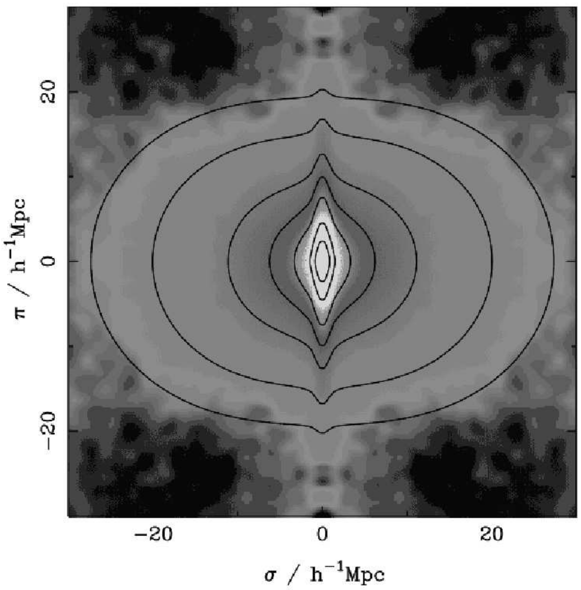

Figure 3. The galaxy correlation function, $\xi(\sigma, \pi)$, for pair separations along the line of sight, π, and in the plane of the sky, σ (Peacock 2002). The amplitude is represented by the grey scale image. The contours for a model with $\beta = 0.4$ and a pairwise dispersion velocity of 400 km s^{-1} are shown. At small angular pair separations, large peculiar velocities along the line of sight in non-linear structures, such as in galaxy groups and clusters, elongate the correlation function. At larger transverse scales, coherent in-fall causes a flattening of the correlation function. The degree of flattening is determined by total mass density and the biasing of the galaxy distribution $\beta = \Omega_m^{0.6}/b = 0.43 \pm 0.07$ (Peacock et al. 2001)

The first public release of about half of the data was made in June 2001 on a set of 4 CD-ROMs. This release contains all the HTML pages and the SQL and associated software needed to setup a database server on a Linux PC. All of the data will soon be available on a CD-ROM/DVD-ROM set, and on-line. The order form for the ROMs and on-line access to the database can be found at `http://www.mso.anu.edu.au/2dFGRS`

More details of the database, including the FITS keywords and SQL parameters, are given in Colless et al. (2001), and can be found on-line at the URL cited above.

4. Science from the 2dFGRS

The science results that have been obtained from the survey are listed in summary form along with references to the papers describing these results in more detail. The galaxy two-point correlation function is described in Figure 3, and the galaxy power spectrum is described in Figure 4.

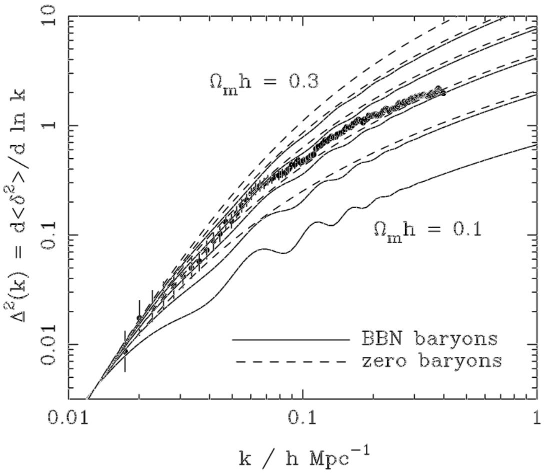

Figure 4. The redshift-space dimensionless power spectrum (Peacock 2002). The points with error bars represent the 2dFGRS results. The lines represent $n = 1$ CDM models for $\Omega_m h = 0.1 - 0.3$. The BBN models assume the big-bang nucleosynthesis value of $\Omega_b h^2 = 0.02$ and $h = 0.7$ A good fit is obtained with the BBN model for $\Omega_m h \approx 0.2$, consistent with the conclusion that the galaxies are unbiased tracers of the mass on large scales.

4.1. Properties of the Galaxy Distribution

- A precise determination of the galaxy power spectrum, quantifying the large-scale structure of the the galaxy distribution on scales up to 300 h^{-1} Mpc (Percival et al. 2001).

- The unambiguous detection of redshift-space distortions due to coherent collapse on large scales, confirming that structures grow through gravitational instability (Peacock et al. 2001).

- Measurements of Ω_m (the mean mass density of the universe) from both the power spectrum and the redshift-space distortions: $\Omega_m = 0.29 \pm 0.05$ (Peacock et al. 2001; Percival et al. 2001)

- The detection of acoustic oscillations in the galaxy power spectrum, resulting from baryon-photon coupling in the early universe (Percival et al. 2001)

- An estimate of the Hubble constant, H_0, and the cosmological constant, λ, from a comparison of the galaxy and CMB power spectra: $H_0 = 72 \pm 7$ km s^{-1} Mpc^{-1} and $\lambda = 0.7 \pm 0.1$ (Efstathiou et al. 2002)

- Measurements of the baryon fraction from the acoustic oscillations in the power spectrum and from a comparison with the CMB power spectrum: $\Omega_b/\Omega_m = 0.15 \pm 0.07$ (Percival et al. 2001; Efstathiou et al. 2002)

- An improved upper limit on the neutrino fraction, $\Omega_\nu/\Omega_m < 0.13$, implying a limit on the total mass of all neutrino species of $m_\nu < 1.8$ eV (Elgaroy et al. 2002).

- The first measurements of the galaxy bias parameter, from the bispectrum of the galaxy distribution alone, and from a comparison of the galaxy and CMB power spectra: $b = 1.00 \pm 0.09$ (Verde et al. 2002; Lahav et al. 2002)

4.2. Properties of the Galaxy Population

- The best determinations to date of the optical and near-IR galaxy luminosity functions (Cole et al. 2001; Norberg et al. 2002)

- The detailed characterization of the variations in the luminosity function with spectral type (Folkes et al. 1999; Madgwick et al. 2002).

- A preliminary determination of the bivariate distribution of galaxies over luminosity and surface brightness (Cross et al 2001).

- The first precise measurement of the dependence of galaxy clustering on both luminosity and spectral type (Norberg et al. 2001, 2002).

- A constraint on the space density of rich clusters from the velocity dispersion distribution for identified clusters (De Propris et al. 2001)

- Separate radio luminosity functions for AGN and star-forming Galaxies (Sadler et al. 2001; Magliocchetti et al. 2002)

- Constraints on the star-formation history of galaxies from the mean spectrum of galaxies in the local Universe (Baldry et al. 2002)

- A measurement of the environmental dependence of star-formation rates of galaxies in clusters (Lewis et al 2002).

5. Conclusions

The 2dFGRS results support the conclusion that the Universe is flat and lambda dominated, as was first indicated by the galaxy counts (Peterson 1993; Yoshii and Peterson, 1995). Together with the CMB measurements, the 2dFGRS results determine the values of the cosmological parameters, $(\Omega_b, \Omega_m, \lambda, h) = (0.04, 0.29, 0.71, 0.72)$, to an accuracy of 10%.

Acknowledgments. The 2dFGRS team acknowledges and thanks the many people at the AAO whose extraordinary efforts have made the survey not only possible but successful.

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