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The 2dF Galaxy Redshift Survey

The 2dF Galaxy Redshift Survey (2dFGRS) produced a three-dimensional map of the distribution of 221000 galaxies covering 5% of the sky and reaching out more than 3 billion lightyears to a redshift $z \approx 0.3$. The survey used the Anglo-Australian Telescope's 2-degree Field facility (2dF), which could observe 400 objects simultaneously over a 2°-diameter field of view. Survey observations began in 1997 and were completed in 2002; the final survey was an order of magnitude larger than any previous redshift survey.

The 2dFGRS yielded the first map of the large-scale structure in the local (low-redshift) universe to probe a statistically representative volume on scales from tens of kiloparsecs to hundreds of Megaparsecs. Analysis of the map gave the first direct evidence that the large-scale structure of the universe grew through gravitational instability, and provided a precise measurement of the mean mass density of the universe. The observed structure also displayed a weak signature produced by the interactions between baryons and photons in the very early universe, providing an estimate of the ratio of baryonic matter to dark matter. The combination of the 2dFGRS observations of the structure in the present-day universe with observations of the structure in the very early universe from the cosmic microwave background (CMB) gave precise measurements of the Hubble constant and the cosmological constant, and provided an improved upper limit for the mass of the neutrino.

The massive sample of galaxies observed by the 2dFGRS has also been used to precisely characterize multi-parameter distributions and relationships within the galaxy population: the distribution of galaxies over luminosity, surface brightness, spectral type, star-formation rate and environment (local density), and the variation in clustering for galaxies of different luminosities and spectral types. The survey also yielded the first measurement of the galaxy bias parameter, which links the fluctuations in the number of galaxies and the amount of dark matter, and is a basic constraint on models of galaxy formation and evolution.

The History of the 2dFGRS

The seed of the 2dFGRS was planted in the late 1980's, when a British astronomy review gave high priority to converting existing telescopes to wide-field science, especially multi-object spectroscopy. For the AAT, the case for such a conversion was greatly strengthened when Roderick Willstrop and Charles Wynne showed that, with suitable correction optics, the telescope could be adapted to permit a 2-degree diameter field of view at the prime focus (Willstrop 1987; Wynne 1989).

The Anglo-Australian Observatory, under Director Russell Cannon and instrumentation scientist Keith Taylor, combined this opportunity with its established strength in robotic multi-object spectroscopy in order to develop a wide-field, multi-object spectrograph: the 2dF facility (Taylor & Gray 1990; Gray et al. 1993). With massive field-correction optics including an atmospheric dispersion compensator, a pair of tumbling focal planes to minimize dead time, 400 optic fibres mounted in magnetic buttons, a fully-robotic positioning system, and end-to-end software for control, configuration, data-taking and reductions, 2dF was, for its time, a visionary instrument. Construction began in 1990.

From its conception, the main scientific driver for 2dF was a massive redshift survey, sampling a representative volume of the universe in fine detail in order to precisely measure fundamental cosmological parameters. The best existing and on-going surveys in the early 1990's (e.g. the IRAS Point Source Catalogue redshift survey and the Las Campanas Redshift Survey) either did not cover sufficiently large volumes to be statistically representative of the large-scale structure, or covered large volumes too sparsely to provide precise measurements. An order of magnitude increase in the volume and sample size of redshift surveys was required to enter the regime of 'precision cosmology'. This idea was developed into a concrete proposal by the founding members of the survey team during 1993 and 1994. The first survey proposal was submitted to the telescope time committees and the AAT Board in 1994, and envisaged a survey of 250000 galaxies over 2000 $\deg^2$ to a magnitude limit of b_J=19.5. The survey was estimated to require 125 nights on the AAT, and was projected to be completed by the end of 1996.

In fact, 2dF was placed on the AAT in November 1995, and the first spectra were taken in mid-1996. Scheduled observations with 2dF at full functionality began in September 1997, and the first major redshift survey observing run occurred in October 1997. Progress with the survey was slow to begin with, but the survey passed 50000 redshifts in mid-1999 and 100000 redshifts in mid-2000 (Colless 1999). The first 100000 redshifts and spectra were released publicly in June 2001 (Colless et al. 2001), and the 200000-redshift mark was achieved towards the end of 2001. The survey observations were completed in April 2002, after 5 years and 272 nights on the AAT.

The 2dF Wide-Field Fibre Spectrograph Facility

As its name implied, the 2dFGRS was tightly coupled to the capabilities of the 2-degree Field facility (2dF) of the AAT. The crucial parameters of 2dF for a massive redshift survey were: (i) the wide (2°-diameter) field of view, which allowed the 1800 deg^2 of the survey to be covered with 900 overlapping fields; (ii) the large number (400) of simultaneous spectra, which allowed the typical number of galaxies in the field of view down to b_J=19.5 to be observed at once; (iii) the 4-metre aperture of the AAT, which allowed redshifts to be measured for galaxies as faint as b_J=19.5 in 1-hour observations; and (iv) the capacity for rapid re-configuration, which meant that there was no dead-time between observations of different fields.

To achieve these complex requirements, a complex instrument was required. All the components of 2dF are contained in the 2dF top-end ring structure, which is mounted at the prime focus of the AAT (see Figure 1).

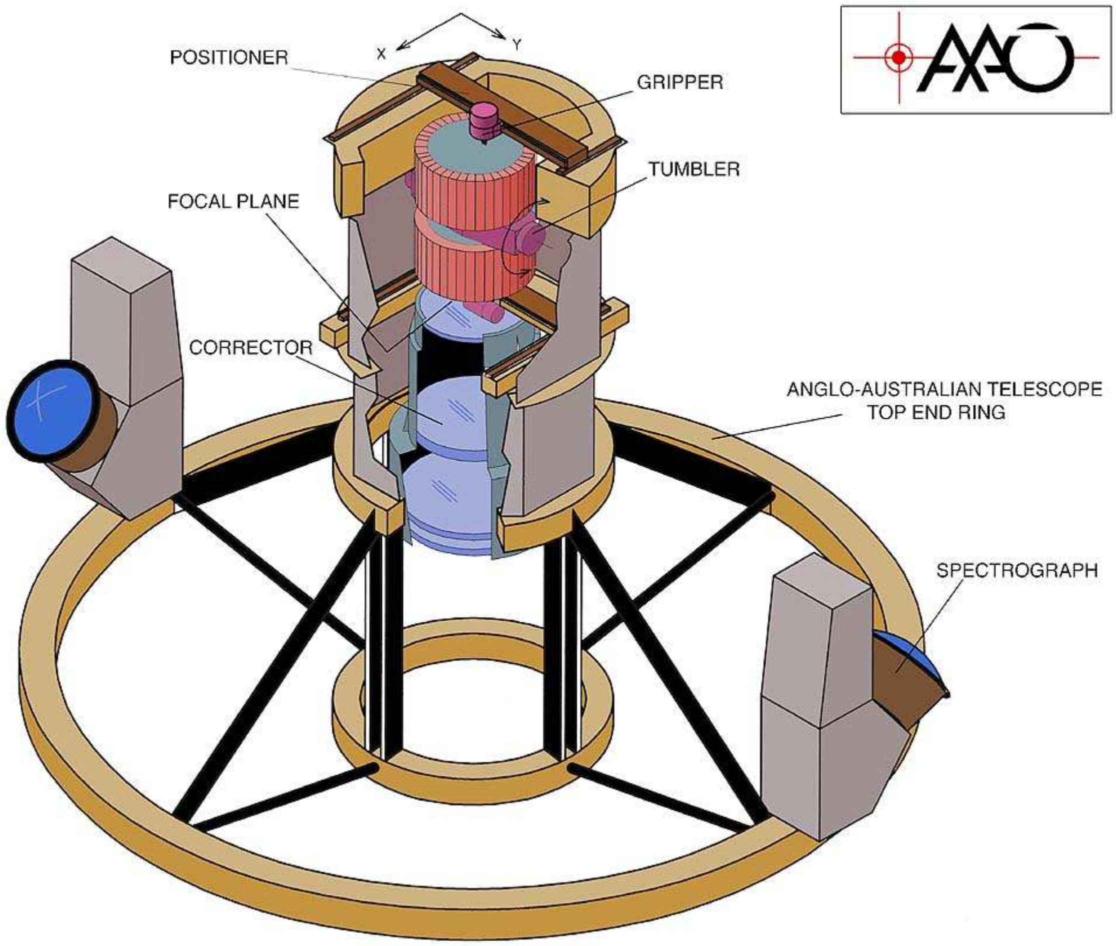

Figure 1. A schematic of the 2dF facility showing the major components of the instrument. Credit: K. Taylor, Anglo-Australian Observatory]

A photon reflected by the AAT's 4-metre primary mirror towards the prime focus encounters, first, the wide-field corrector optics (including an atmospheric dispersion corrector) that provide a 2°-diameter field of view with good imaging properties; then it is collected at the focal plan by the fibre buttons that route it down the optic fibres;

finally, it enters one of the twin spectrographs, each of which measures the spectra from 200 fibres at a time. The total system efficiency is about 5%.

The fibre buttons are magnetically attached to a metal plate in the focal plane. They are positioned on the plate by a high-precision robot, which moves over the plate on an X-Y stage and has a gripper arm that can be raised or lowered to pick or place a button on the plate. The robot can position a fibre button on the plate with a precision of 0.3 arcsec (20 μm) in 6 seconds. In order to maximize observing efficiency there are two sets of fibre buttons, and the plates on which they sit are tumbled between the focal plane position and the robot position. This allows the robot to configure the fibres on one plate while the fibres on the other plate are observing the sky.

A full technical description of the 2dF facility is given by Lewis et al. (2002).

Survey Observations

The source catalogue for the 2dFGRS survey was a revised and extended version of the APM galaxy catalogue (Maddox et al. 1990), which was created by scanning the photographic plates of the UK Schmidt Telescope Southern Sky Survey. The survey targets were chosen to be galaxies with extinction-corrected magnitudes brighter than b_J=19.45. The galaxies were distinguished from stars by an image classification algorithm that was conservatively designed to include all galaxies at the expense of also including a 5% contamination of the sample by stars.

The main survey regions were two declination strips, one in the southern Galactic hemisphere spanning $80° \times 15°$ around the South Galactic Pole (the SGP strip), and the other in the northern Galactic hemisphere spanning $75° \times 10°$ along the celestial equator (the NGP strip); in addition, there were 99 individual 2dF 'random' fields spread over the southern Galactic cap (see Figure 2). The survey covers approximately 1800°, and has a median redshift depth of z=0.11. An adaptive tiling algorithm was used to optimally place the 900 2dF fields over the survey regions, giving a highly complete and uniform sample of galaxies on the sky.

Redshifts were measured from 2dF spectra that covered the range from 3600Å to 8000Å at a resolution of 9.0Å. Redshift measurements were obtained both from cross-correlation with template spectra and from fitting emissioning lines. All redshifts were visually checked and assigned a quality parameter Q in the range 1–5; accepted redshifts ($Q \geq 3$) were found to be 98% reliable and to have a typical uncertainty of 85 km s^{-1}. The overall redshift completeness for accepted redshifts was 92%, although this varied with magnitude.

Figure 3 shows a thin slice through the three-dimensional map of over 221000 galaxies produced by the 2dGRS. The observer is at the centre of the map, with redshift increasing towards the edge and angle on the sky (R.A.) marked around the circumference. This 3°-thick slice passes through both the NGP strip (at left) and the SGP strip (at right). The decrease in the number of galaxies towards higher redshifts is an effect of the survey selection by magnitude—only intrinsically more luminous galaxies are brighter than the survey magnitude limit at higher redshifts. The clusters, filaments, sheets and voids making up the large-scale structures in the galaxy distribution are clearly resolved. Importantly, there are many such structures visible in the figure, demonstrating that the survey volume comprises a representative sample of the universe.

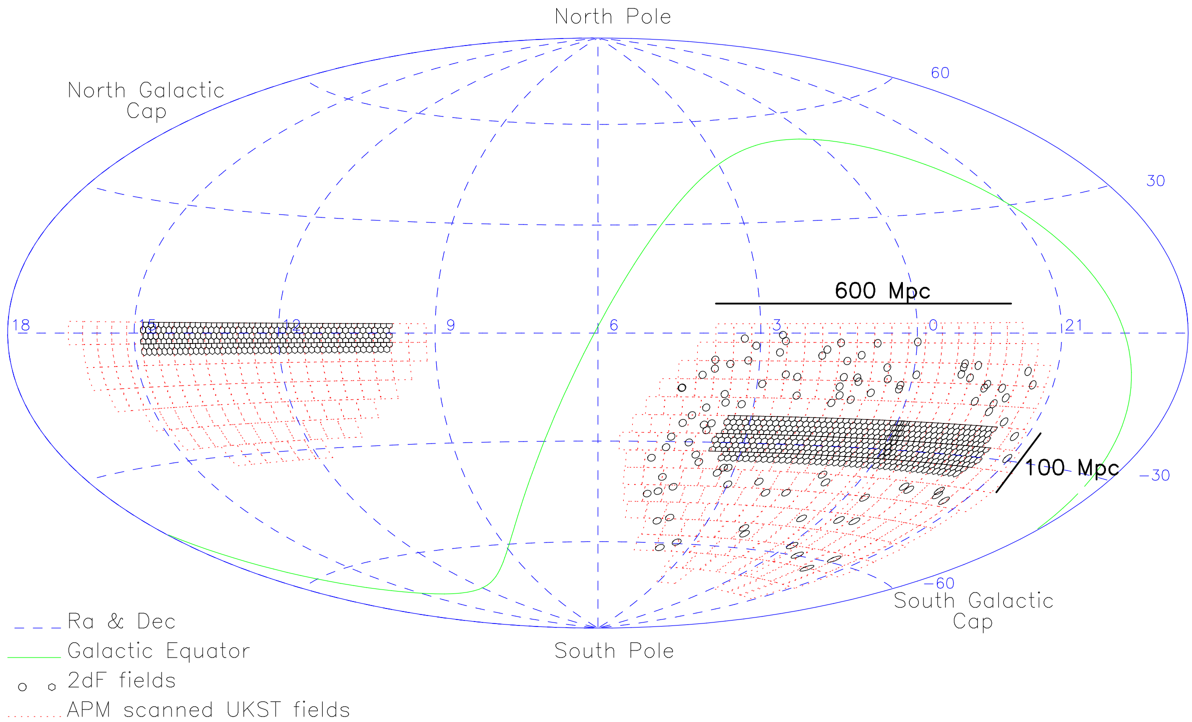

Figure 2. A map of the sky showing the locations of the two 2dFGRS survey strips (NGP strip at left, SGP strip at right) and the random fields. Each 2dF field in the survey is shown as a small black circle; the sky survey plates from which the source catalogue was constructed are shown as small red squares. The scale of the strips at the typical redshift of the survey is indicated. [Credit: S.J. Maddox, University of Nottingham]

Cosmological Results

Although survey observations finished in April 2002, as of this writing the scientific analysis of the survey is still in progress. So far the main results to emerge have been cosmological, in keeping with the primary goals of the survey as it was envisaged a decade ago when 2dF was being built.

The first step in this analysis is a statistical characterization of the large-scale structure in the galaxy distribution, which in most cosmological models is fully described, at least on the largest scales, by just two quantities: the mean density and the variation in the typical size of the fluctuations in the density as a function of scale. The latter is best quantified on large scales by the power spectrum of the galaxy distribution, which Percival et al. (2001) measured from the 2dFGRS on scales up to $300\,h^{-1}\,$Mpc. The shape of the power spectrum is consistent with a cold dark matter (CDM) model having a shape parameter $\Gamma = \Omega_M h = 0.20 \pm 0.03$, which, for a Hubble constant around $70\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$ (i.e. $h \approx 0.7$), implies a mean mass density $\Omega_M \approx 0.3$. The power spectrum also showed the weak signature of acoustic oscillations produced by baryon-photon coupling in the early universe, allowing Percival et al. to also estimate the mass fraction in baryons, $\Omega_b/\Omega_M = 0.15 \pm 0.07$.

The galaxy distribution on intermediate scales provides another measure of the mass density, and also a test of the fundamental assumption that structures grow due to gravitational instability. Under this paradigm small-scale structures are undergoing non-linear collapse, while on larger scales structures are collapsing coherently. These effects lead to a characteristic distortion of the galaxy distribution observed in redshift space, with the small, high-density clusters of galaxies stretched out along the line of

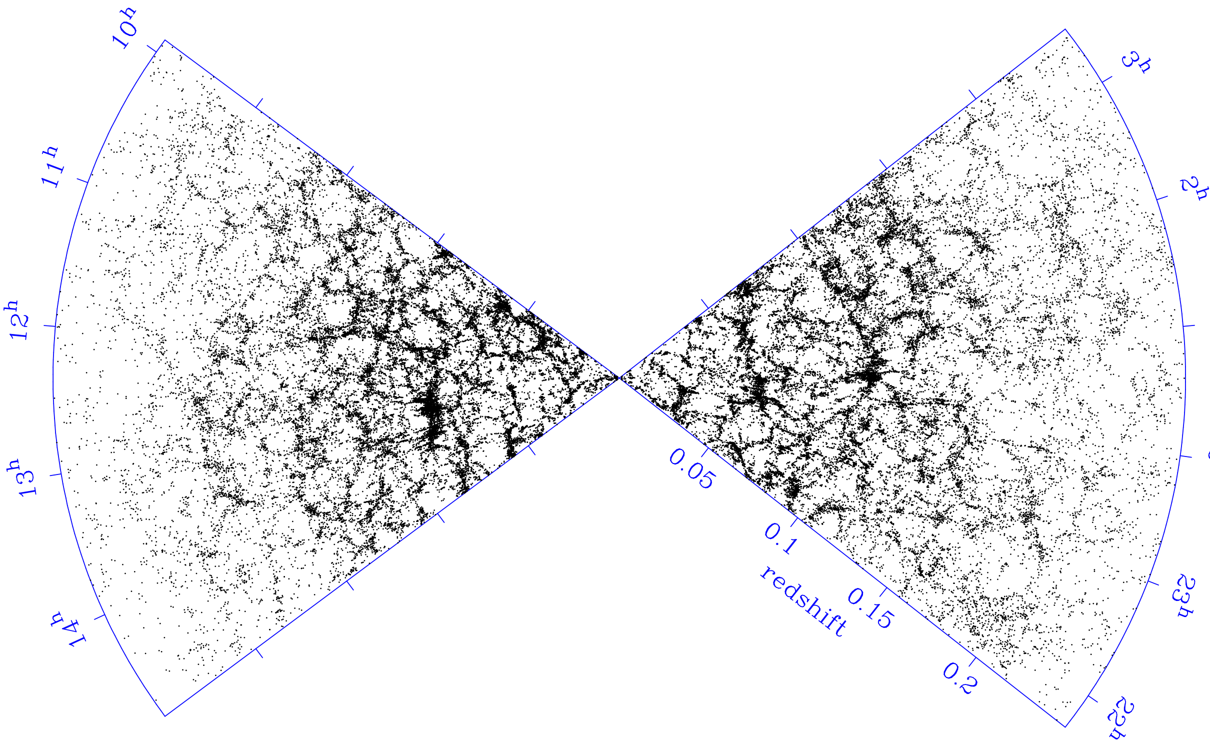

Figure 3. A 3°-thick slice through the 2dF Galaxy Redshift Survey map. The slice cuts through the NGP strip (at left) and the SGP strip (at right). It contains 63000 galaxies and shows the large-scale structures in the galaxy distribution. [Credit: J.A. Peacock, University of Edinburgh]

sight and the larger, moderate-density filaments and sheets compressed along the line of sight. The first unambiguous detection of these redshift-space distortions was obtained from the 2dFGRS by Peacock et al. (2001), confirming that present-day structures are due to the gravitational amplification of small initial density fluctuations. The amplitude of the distortion depends on the quantity $\beta = \Omega^{0.6}/b$, where b parametrizes the bias of the galaxies with respect to the overall mass distribution. By measuring the compression of the galaxy two-point correlation function along the line of sight, Peacock et al. obtained $\beta = 0.54 \pm 0.09$ for galaxies with luminosities similar to the Milky Way. If such galaxies are relatively unbiased tracers of the galaxy distribution (i.e. $b \approx 1$), this also implies $\Omega_M \approx 0.3$.

Stronger constraints on these and other fundamental cosmological parameters were obtained by combining the power spectrum of the present-day galaxy distribution from the 2dFGRS with the power spectrum of the mass distribution at very early times derived from observations of the anisotropies in the CMB. Such analyses have been carried out by Efstathiou et al. (2002) and Percival et al. (2002), and show that the universe has a flat or near-flat geometry ($\Omega_k = 0 \pm 0.05$), with a low total matter density ($\Omega_M = 0.31 \pm 0.06$) and a large positive cosmological constant ($\Omega_\Lambda = 0.69 \pm 0.06$, consistent with the independent estimates from observations of high-redshift supernovae). The physical densities of cold dark matter and baryons are $\omega_c = \Omega_c h^2 = 0.12 \pm 0.01$ and $\omega_b = \Omega_b h^2 = 0.022 \pm 0.002$; the latter agrees very well with the constraints from Big Bang nucleosynthesis. The joint 2dFGRS+CMB analysis also provided an estimate of the Hubble constant ($H_0 = 67 \pm 5\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$) that is independent of, but in excellent accord with, the results from the Hubble Space Telescope Key Project. Elgaroy et al. (2002) showed that these combined constraints place a strong upper limit on the neutrino mass fraction, $\Omega_\nu/\Omega_M < 0.13$ (95% confidence), which translates to an upper limit on the total neutrino mass (summed over all species) of $m_\nu < 1.8\,\mathrm{eV}$.

Another first for the 2dFGRS was the measurement of the bias, b, between the galaxy distribution and the underlying matter distribution, defined as the square root of the ratio of the galaxy and matter power spectra. Lahav et al. (2002) measured this ratio using the 2dFGRS and CMB power spectra, and found that for galaxies with characteristic (L^*) luminosities the bias parameter is $b^* = 0.96 \pm 0.08$. An independent analysis by Verde et al. (2002), using only the 2dFGRS and based on the higher-order correlations of the galaxy distribution in the quasi-linear regime, obtained a very similar result: $b^* = 0.92 \pm 0.11$. The conclusion is that L^* galaxies are nearly unbiased tracers of the mass distribution. However, Norberg et al. (2001, 2002a) showed that the bias parameter does vary with luminosity and spectral type, ranging from $b = 1.5$ for bright, early-type galaxies to $b = 0.8$ for faint, late-type galaxies.

The measurement of cosmological parameters from the 2dFGRS has made a significant contribution to shaping the current consensus model for the fundamental properties of the universe that has emerged from a range of independent observations, including the measurements of the CMB anisotropies, the distances to high-redshift supernovae and Big Bang nucleosynthesis.

Properties of the Galaxy Population

Alongside these cosmological studies, the 2dFGRS has also yielded a wide range of results on the properties of the galaxy population, and provided strong new constraints for models of galaxy formation and evolution. Highlights in this area to date include: (1) Precise determinations of the optical and near-IR galaxy luminosity functions (Cole et al. 2001; Norberg et al. 2002b). (2) A detailed characterization of the variations in the luminosity function with spectral type (Folkes et al. 1999; Madgwick et al. 2002). (3) A determination of the bivariate distribution of galaxies over luminosity and surface brightness (Cross et al. 2001). (4) A constraint on the space density of rich clusters of galaxies from the velocity dispersion distribution for identified clusters (De Propris et al. 2001). (5) Separate radio luminosity functions for AGN and star-forming galaxies (Sadler et al. 2001; Magliocchetti et al. 2002). (6) Constraints on the star-formation history of galaxies from the mean spectrum of galaxies in the local universe (Baldry et al. 2002). (7) A measurement of the environmental dependence of star-formation rates of galaxies in clusters (Lewis et al. 2002).

These results are just a fraction of the information that can be extracted from the 2dFGRS on the properties of galaxies and their relation to the large-scale structure of the galaxy distribution. Many more results are still to emerge from analysis of the survey, and from combining the 2dFGRS with other large surveys and with detailed follow-up observations.

Bibliography

The 2dF Galaxy Redshift Survey web pages (`http://www.mso.anu.edu.au/2dFGRS`) contain detailed information about the survey, a gallery of images, an access point for the survey database, and a list of all 2dFGRS publications. The most relevant publications, referenced in this article, are as follows:

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Cross N. et al., 2001, MNRAS, 324, 825
De Propris R. et al., 2002, MNRAS, 329, 87
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Verde L. et al., 2002, MNRAS, 335, 432
Willstrop R.V., 1987, MNRAS, 229, 143
Wynne C.G., 1989, MNRAS, 236, 47P

The 2dFGRS was carried out by a team of 30 Australian and British astronomers, led by Matthew Colless (The Australian National University), Richard Ellis (University of Cambridge and the California Institute of Technology), Steve Maddox (Universities of Cambridge and Nottingham) and John Peacock (University of Edinburgh). A full list of team members can be found on the 2dFGRS web pages.

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