The 6dF Galaxy Survey: First Data Release

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Abstract.
The 6dF Galaxy Survey (6dFGS) is currently measuring the redshifts of around 170 000 galaxies and the peculiar velocities of a 15 000-member sub-sample. It will be the largest redshift survey of the local universe and more than an order of magnitude larger than any peculiar velocity survey to date. When complete, it will cover essentially the entire southern sky around a mean redshift of $z = 0.05$. Central to the survey is the Six-Degree Field (6dF) multi-fibre spectrograph, an instrument able to record 150 simultaneous spectra over the 5.7°-field of the UK Schmidt Telescope. Targets have been drawn from the 2MASS Extended Source Catalog (XSC) to include all galaxies brighter than $K_{\rm tot} = 12.75$, supplemented by 2MASS and SuperCOSMOS galaxies that complete the sample to limits of $(H, J, r_F, b_J) = (13.05, 13.75, 15.6, 16.75)$. Here we describe the implementation of the survey and the procedures used to select sources and determine redshifts. We also describe early results utilising the First Data Release of $\sim 45\,000$ redshifts. There is an online database of 6dFGS data accessible from the 6dFGS web site (http://www.mso.anu.edu.au/6dFGS).

1. Introduction

The 6dF Galaxy Survey (6dFGS; Jones et al. 2004) is a dual redshift/peculiar velocity survey that aims to secure the redshifts of 150 000 galaxies over the southern sky, and the peculiar velocities of a 15 000-galaxy subset. The main target catalogues are selected from the Two Micron All Sky Survey (2MASS; Jarrett et al. 2000) using total galaxy magnitudes in JHK. There are several advantages of choosing galaxies in these bands. First, the near-infrared spectral energy distributions (SEDs) of galaxies are, in general, dominated by the near-infrared light of their old stellar populations, which also provides the best photometric estimator of their stellar mass. Traditionally, surveys have selected target galaxies in the optical where galaxy SEDs are dominated by younger, bluer stars, and so are more indicative of the star-formation rate than the total stellar mass. Second, the E/S0 galaxies that will provide the best targets for Fundamental Plane peculiar velocity measures represent the largest fraction by galaxy type of near-infrared-selected samples. Finally, the effects of dust extinction are minimal at long wavelengths. In the target galaxies, this means that the total near-infrared luminosity is not dependent on galaxy orientation and so provides a reliable measure of galaxy mass. In our own Galaxy, it means the 6dFGS can map the local universe nearer to the plane of the Milky Way than would be possible through optical selection.

The aims of the redshift survey are: (1) To take a near-infrared selected sample of galaxies and determine their luminosity function as a function of environment and galaxy type. From these, the stellar mass function and mean stellar fraction of the local universe can be ascertained and compared to the integrated stellar mass inferred from measures of cosmic star formation history, extending the work of Cole et al. (2001), Kochanek et al. (2001) and Bell et al. (2003). (2) To measure galaxy clustering on both small and large scales and its relation to stellar mass. In doing so, the 6dFGS will provide new insight into the scale-dependence of galaxy biasing and the relationship between the integrated star-formation histories of galaxies and the large-scale structure of the dark matter. (3) To determine the power spectrum of this galaxy clustering on scales similar to those spanned by the 2dF Galaxy Redshift Survey and Sloan Digital Sky Surveys. (4) To delineate the distribution of galaxies in the nearby universe. The 6dFGS will not cover as many galaxies as either the 2dF Galaxy Redshift Survey or Sloan Digital Sky Survey. However, because it is a large-volume survey of nearby galaxies, it provides the ideal sample on which to base a peculiar velocity survey. In this respect, the complete 6dFGS will be more than ten times larger in number and cover twice the volume of the PSCz Survey (Saunders et al. 2000), previously the largest survey of the local universe. (5) To furnish a complete redshift catalogue for future studies in this regime. Precise distance measures impose stronger demands on signal-to-noise than do redshifts. With such higher quality spectra, it it is also possible to infer, by comparison with stellar population models, properties of the underlying stellar population such as ages and chemical abundances. Having such measurements along with the galaxy mass and knowledge of its local envrionment, will afford unprecedented opportunities to understand the processes driving galaxy formation and evolution.

This redshift catalogue will provide the basis for a volume-limited sample of early-type galaxies for the peculiar velocity survey. The aims of the peculiar velocity survey are: (1) A detailed mapping of the density and peculiar velocity fields to around 15000 $\mathrm{km\,s^{-1}}$ over half the local volume. (2) The inference of the ages, metallicities and star-formation histories of E/S0 galaxies from the most massive systems down to dwarf galaxies. The influence of local galaxy density on these parameters will also be of key interest to models of galaxy formation. (3) To understand the bias of galaxies (number density versus total mass density field) and its variation with galaxy parameters and environment.

2. The Six-Degree Field Instrument

Central to the 6dFGS is the Six-Degree Field multi-object fibre spectroscopy facility, (hereafter referred to as 6dF). 6dF can obtain up to 150 simultaneous spectra across the 5.7°-diameter field of the UKST. Fuller descriptions of the 6dF instrument have been given elsewhere (Parker et al. 1998, Watson et al. 2000, Saunders et al. 2001).

Unlike 2dF, the 6dF positioning robot is off-telescope, in a special enclosure on the dome floor. Two identical field plate units are available, allowing one to be mounted on the telescope taking observations whilst the other is being configured by the 6dF robot. Each 100μm (6.7$''$) science fibre is terminated at the input end by a 5 mm diameter circular button, containing an elongated SF2 prism to deflect the light into the fibre and a strong rare-earth magnet for adhesion to the field plate. Targets closer than 5.7$'$ on the sky cannot be simultaneously configured due to the clearances required to avoid collisions and interference between buttons. A full field configuration takes around 30-40 minutes depending on target disposition and target numbers, plus about half this time to park any prior configuration. This is less than the 1.5 - 2.5 hours (depending on conditions) spent by a configured field plate in the telescope.

All 6dFGS data taken prior to October 2002 used 600V and 316R reflection gratings, covering 4000–5600 Å and 5500–8400 Å respectively. Subsequent data use Volume-Phase transmissive Holographic (VPH) 580V and 425R gratings with improved efficiency, focus, and data uniformity. The wavelength coverage is 3900–5600 Å and 5400–7500 Å, and the grating and camera angles (and hence dimensionless resolutions) are identical. The peak system efficiency (good conditions and acquisition, wavelengths near blaze, good fibres) is 11%, but can be much less.

The UK Schmidt with 6dF is well-suited to low to medium resolution spectroscopy of bright ($V < 17$), sparsely distributed sources (1 to 50 deg^{-2}). It fills the gap left open by 2dF for large, shallow surveys covering a significant fraction of the total sky. In terms of the $A\Omega$ (telescope aperture $\times$ field of view) figure-of-merit, UKST/6dF is similar to AAT/2dF and Sloan.

3. Survey Design

The original science drivers for the 6dF project were an all-southern-sky redshift survey of NIR-selected galaxies, and a large peculiar velocity survey of early-type galaxies. Three instrumental considerations led to the observations for these projects being merged. First was the need to cover the sky at least twice over in order to reach acceptable levels of completeness. Second was the need to observe each field with two grating set-ups in order to achieve the required wavelength coverage and resolution. Third was the constraint of overheads and robot configuring times that meant that observations less than 1-2 hours/field were not an efficient use of the telescope. Together, these factors meant that the redshift survey would necessarily take longer than originally envisaged. However, careful consideration of the effects of signal-to-noise and resolution on velocity width measurements (see Wegner et al. 1999), led us to conclude that for the luminous, high surface brightness galaxies expected to dominate the peculiar velocity survey, the resolution and signal-to-noise expected from the redshift survey observations (in some case repeated to increase S/N), would in general allow velocity widths to be determined to the required accuracy. Therefore, in early 2001 a decision was made to merge the observations for the two surveys.

3.1. Redshift Survey

The primary redshift (z-survey) sample is a magnitude-limited selection drawn from the 2MASS Extended Source Catalog, version 3 (2MASS XSC; Jarrett et al. 2000). Since the survey is attempting a 'census' of the local Universe, we want to avoid any bias against lower-surface-brightness galaxies, and ideally we would use total magnitudes. The 2MASS data does not have the depth nor resolution to derive robust total magnitudes for galaxies at low galactic latitudes. include total magnitudes. However, it does contain very robust isophotal magnitudes ($K_{\rm iso}$) and diameters to an elliptical isophote of $\mu_K = 20^m$arcsec^{-2}. We found that we were able to make a simple surface-brightness correction to these standard isophotal magnitudes, which gave an excellent approximation to the total magnitudes, where they were reliably determined for high-latitude galaxies:

$$K_{\rm tot} = K_{\rm iso} - 1.5 \exp\left[1.25 \times (\overline{\mu_{K20}} - 20)\right]. \quad (1)$$

Here, $\overline{\mu_{K20}}$ is the mean surface brightness within the $\mu_K = 20$ elliptical isophote, and with a maximum allowed correction of 0.5^m. This 'corrected' isophotal magnitude was also extremely robust to stellar contamination. A latitude cut of $|\,b\,| \geq 10^\circ$ was imposed, mostly because extinctions closer to the plane would demand much greater integration times. The sample was limited to the southern hemisphere ($\delta < 0^\circ$).

Our final selection was then 113 988 galaxies with $K_{\rm tot} < 12.75$, corresponding approximately to $K_{20} < 13^m$ for typical K-selected galaxies. The mean surface density of this primary sample is 7 deg^{-2}. Thirteen other smaller extragalactic samples are merged with the primary sample. These include secondary 2MASS selections down to $H_{\rm tot} = 13.05$ and $J_{\rm tot} = 13.75$ over the same area of sky, constituting an additional $\sim$ 5 000 sources. Optically-selected sources from the SuperCOSMOS catalogue (Hambly et al. 2001) with $r_{\rm F} = 15.6$ and $b_{\rm J} = 16.75$, $|\,b\,| > 20^\circ$ were included, constituting a further $\sim$ 20 000 galaxies. In total there are 167 133 objects with field allocations of which two-thirds are represented by the near-infrared-selected sample. Literature redshifts have been incorporated into the redshift catalogue, 19 570 of these from ZCAT (Huchra et al. 1999) and 8 444 from the 2000 deg^2 in common with the 2dF Galaxy Redshift Survey (Colless et al. 2001).

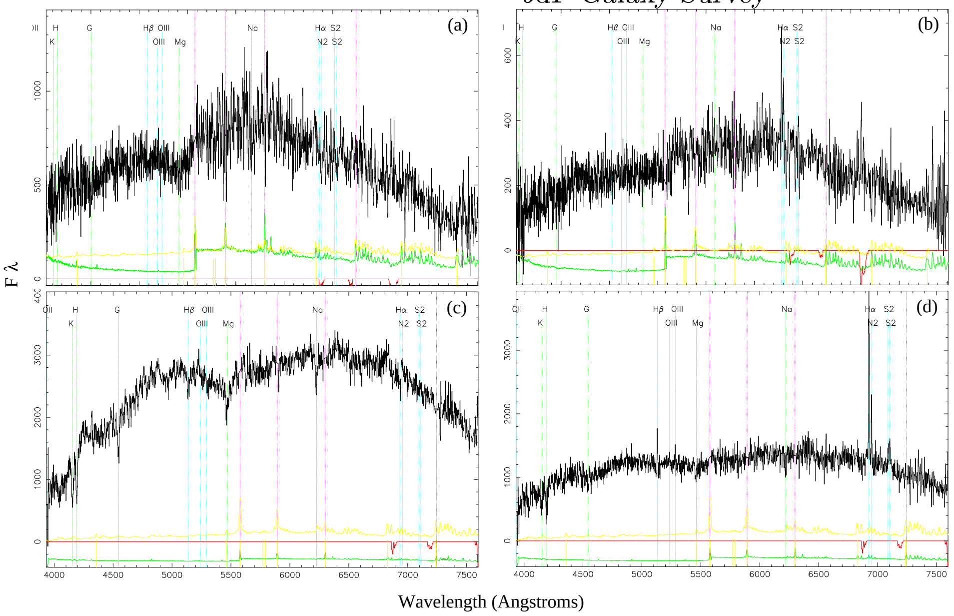

Figure 1. Examples of galaxy spectra from the 6dFGS exhibiting a range of types and redshift quality Q: (a) $Q = 3$ ABS at $z = 0.04601$. (b) $Q = 3$ EMI at $z = 0.03377$. (c) $Q = 4$ ABS at $z = 0.05645$. (d) $Q = 4$ EMI at $z = 0.05344$. Here, EMI refers to emission-line redshifts (and qualities), and ABS refers to absorption line determinations. Major absorption and emission-line features in the spectra have been labelled.

3.2. Peculiar Velocity Survey

The goal of the peculiar velocity (v-survey) is to measure peculiar velocities for an all-southern-sky sample of galaxies. In principle, we can extend the redshift field to the northern hemisphere by including PSCz and other northern z-surveys (*e.g.* Branchini et al. 1999, Huchra et al. 1999). Peculiar velocities are measured for early-type galaxies through the Fundamental Plane (FP) parameters from 2MASS images and 6dF spectroscopy to give velocity dispersions. The v-survey sample consists of all early-type galaxies from the primary z-survey sample that are sufficiently bright to yield precise velocity dispersions. Because we cover the sky twice, suitable candidate galaxies (selected on the basis of either 2MASS morphology or first-pass 6dF spectroscopy) can be observed a second time in order to extend the v-survey sample to fainter limits. Based on the high fraction of early-type galaxies in the K-selected sample and the signal-to-noise ratio obtained in our first-pass spectroscopy, we expect to measure distances and peculiar velocities for 15 000 galaxies with $cz < 15\,000\,\mathrm{km\,s^{-1}}$. When linked with the *predicted* peculiar velocities from all-sky redshift surveys like the PSCz (Branchini et al. 1999), a value for Ω can be found that is independent of CMB measurements.

4. Observations and Reduction

The observing strategy typically allows 3-5 survey fields to be observed on a clear night, depending on season. With 75% of the available dark and grey time on the UKST assigned to 6dFGS, (amounting to 175 nights per year), and an average clear fraction of 60%, we typically observe about 400 fields per year. The observational strategy is to divide the sky into three declination strips. Initially, the survey has concentrated on the $\delta = -30^\circ$ declination strip (actually $-42^\circ < \delta < -23^\circ$); the equatorial strip ($-23^\circ < \delta < 0^\circ$) will be done next, and then finally the polar cap ($\delta < -42^\circ$). The middle strip has been largely completed and progress on the equatorial strip is well underway.

Each field is observed with both V and R gratings, that are later spliced to reconstruct a single spectrum from these two observations. Integrations are a minimum of 1 hr for the V spectrum and 0.5 hr for the R spectrum, although these times are increased in poor observing conditions. This gives spectra with typical S/N around 5 to 10 pixel^{-1}, yielding about 90% redshift completeness.

The reduction of the spectra uses a modified version of the `2DFDR` package developed for the 2dF Galaxy Redshift Survey. Unlike 2dF data, tramline fitting is done completely automatically, using the known gaps in the fibres to uniquely identify the spectra with their fibre number. The extracted spectra for each field are combined, usually weighted by S/N to cope with variable conditions. The S/N is computed at this stage, and a S/N per pixel of around 10 in each of V and R frames usually indicates a satisfactorily observed field. The resulting V and R spectra for each source are then spliced together, using the overlapping region to obtain their relative scaling.

Redshifting is done using a modified version of the semi-automated redshifting `RUNZ` software used for the 2dF Galaxy Redshift Survey (Colless et al. 2001). Each automated redshift is checked visually to decide whether the software has made an accurate estimate or been misled by spurious spectral features. Such features are typically due to fibre interference patterns or poor sky subtraction and are difficult to identify through software, although easily recognisable to a human operator. The final redshift value is assigned a quality, Q, between 1 to 4 where $Q = 3$ or 4 for redshifts included in the final catalogue. $Q = 4$ represents a reliable redshift while $Q = 3$ is assigned to probable redshifts; $Q = 2$ is reserved for tentative redshift values and $Q = 1$ for spectra of no value. Figure 1 shows a few examples of galaxy spectra across the range of redshift quality, for both emission and absorption-line spectra.

Figure 2 shows the relationship between redshift quality Q and mean signal-to-noise of the spectra that yielded them. The vast majority (76%) of the 6dFGS redshifts have $Q = 4$ from spectra with a median signal-noise of 9.4 pixel^{-1}. For $Q = 3$ redshifts the median signal-to-noise ratio drops to 5.3 pixel^{-1}, indicating minimum of range of redshift-yielding spectra. In both cases, note the long tail to higher signal-to-noise values. The median signal-to-noise ratio for $Q = 2$ redshifts (6.3 pixel^{-1}) is slightly higher than that for $Q = 3$ (5.3 pixel^{-1}). This is due to the significant number of Galactic sources such as stars and planetary nebulae, which produce high signal-to-noise spectra, but are assigned $Q = 2$ on account of their zero redshift. The Galactic sources will re-assigned to $Q = 3$ or 4 (as appropriate) on a later pass through the dataset.

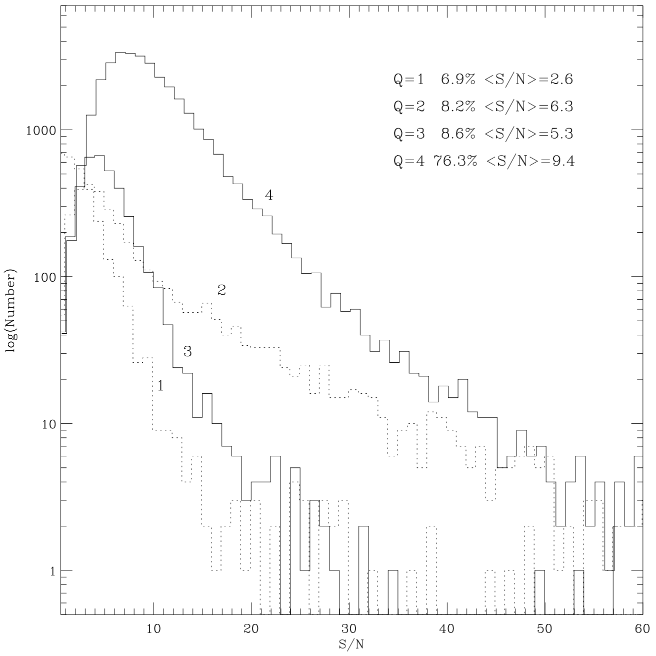

Figure 2. Distribution of signal-to-noise for each class of redshift quality ($Q = 1$ to 4) for the 6dFGS.

5. First Data Release

Between January 2002 and July 2003 the 6dF Galaxy Survey Database compiled 52 048 spectra from which 46 474 unique galaxy redshifts were derived. The numbers of spectra with redshift quality $Q \geq 3$ were 43 945 for the full set and 39 649 for the unique redshifts. Of the 174 442 total galaxies in the target sample, 28 014 had existing literature redshifts: 19 570 from the ZCAT compilation (Huchra et al. 1999) and 8 444 from the 2dF Galaxy Redshift Survey (Colless et al. 2001). Of the 113 988 K_s-selected sources, there are 32 156 6dF-measured redshifts of redshift quality $Q \geq 3$, plus a further 21 151 existing literature redshifts. Around 3% are stars, 1% are other Galactic sources, and 11% failed to yield a redshift.

Data from 524 fields have contributed to the first data release. As shown in Fig. 3 the majority of these occupy the central declination strip between $-42° < \delta < 23°$. Overall there are 1564 on the sky: 547 in the equatorial strip, 595 in the central strip, and 422 in the polar region.

The *field completeness* is the ratio of acceptable redshifts in a given field to initial sources, and hence is only relevant to targets observed with 6dF. It also excludes Galactic features like stars and ISM. Figure 4(*left*) shows the distribution of field completeness from the first 524 fields and its cumulate. This demonstrates that the redshift success rate of 6dF is good, with both the median and mean completeness around 90%. The distribution of 6dFGS redshifts ex-

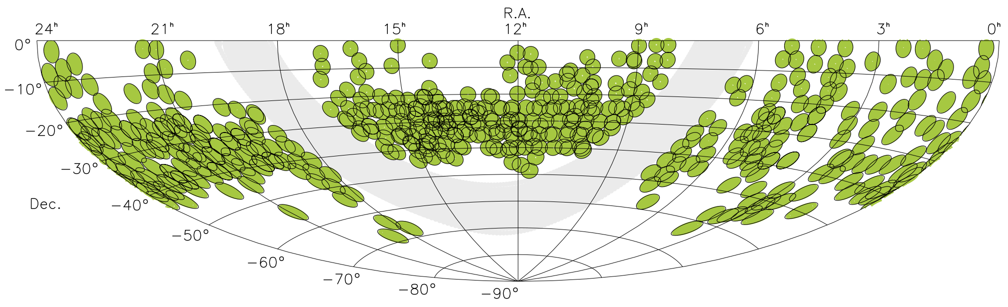

Figure 3. Location of the observed fields contributing redshifts to the First Data Release.

hibits the classic shape for magnitude-limited surveys of this kind (Fig. 4(*right*)). The median survey redshift, $\langle cz \rangle = 16\,008\ \mathrm{km\,s^{-1}}$ ($\bar{z} = 0.055$), is about half that of the 2dFGRS or SDSS surveys.

Figure 5 shows the radial distribution of galaxies across the southern sky, projected within $\Delta\delta = 10°$ declination slices. No 6dFGS galaxies lie within galactic latitude $|\,b\,| \leq 10°$. The 6dFGS is also clumpier than optically-selected redshift surveys such as 2dFGRS and SDSS. This is because the near-infrared selection is biased towards early-type galaxies, which cluster more strongly than spirals.

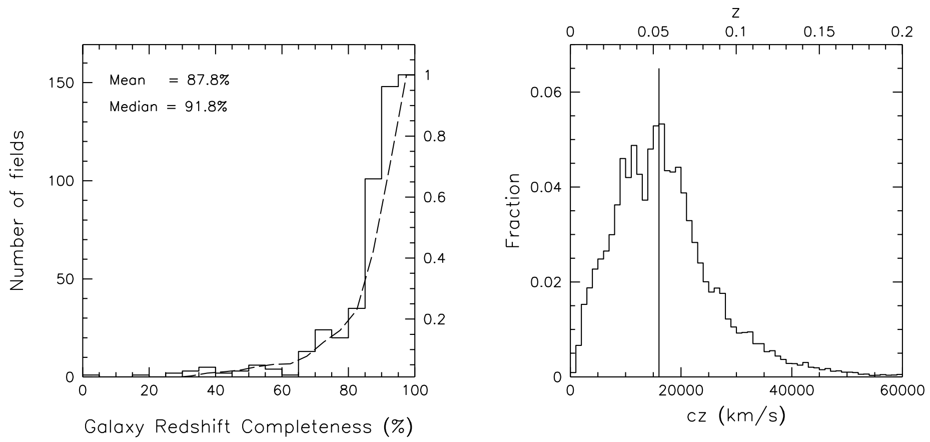

Figure 4. (*left*) Galaxy redshift completeness by field. The dashed line indicates the cumulative fraction according to the right-hand axis. (*right*) Distribution of redshifts for the 6dF First Data Release galaxies with redshift quality $Q \geq 3$ and $cz > 600\ \mathrm{km\,s^{-1}}$.

6. 6dFGS Online Database

Data from the 6dF Galaxy Survey are publicly accessible through an online database at `http://www-wfau.roe.ac.uk/6dFGS/`, and maintained by the Wide

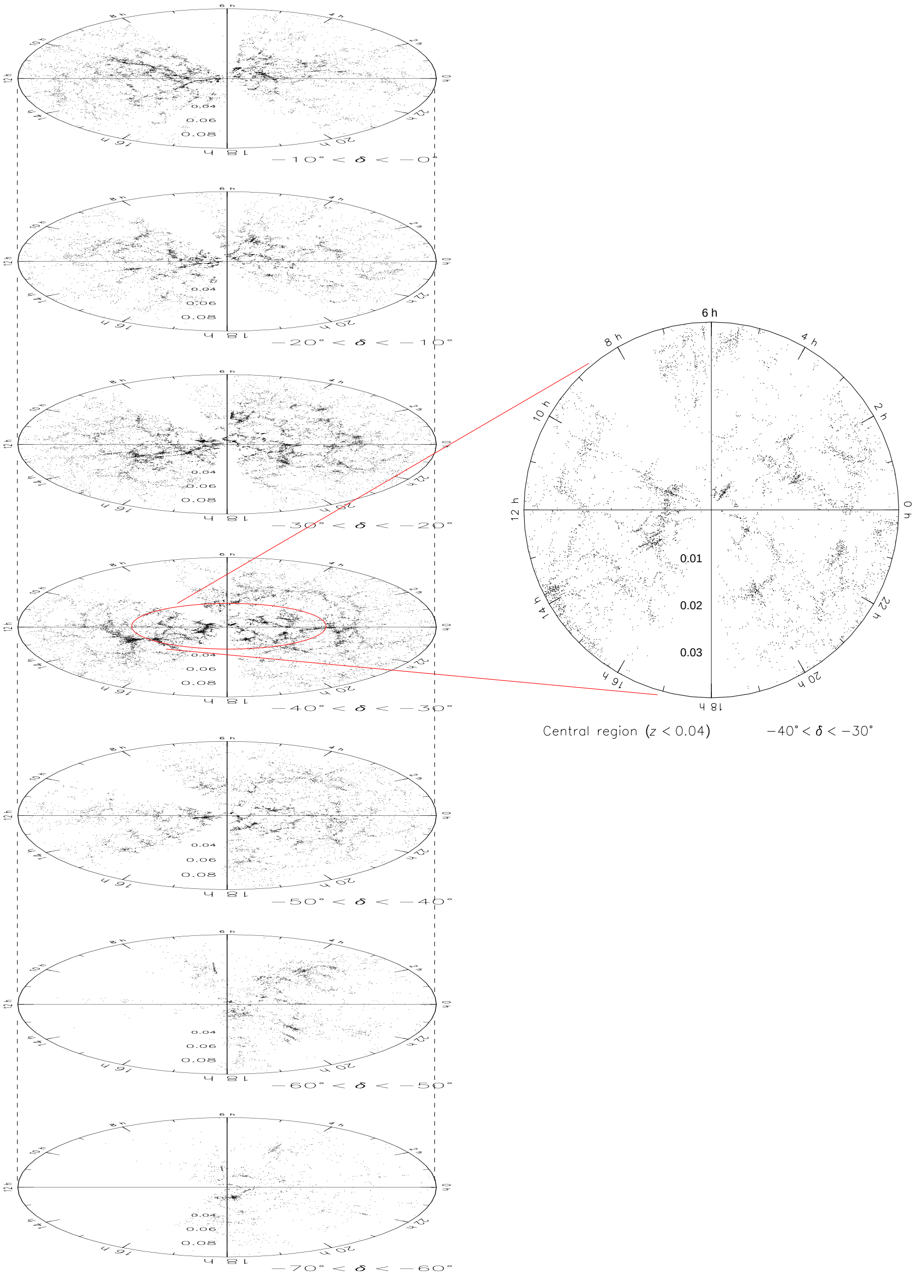

Figure 5. Spatial redshift distribution divided into discs, each spanning a 10° range in declination. The inset shows an expanded view of the central region of the $-40° < \delta < -30°$ slice.

Field Astronomy Unit of the Institute for Astronomy, University of Edinburgh. The design of the database is similar to that used for the 2dF Galaxy Redshift Survey in that parameterised data are stored in a relational database. Each `TARGET` object is also represented by a multi-extension FITS file which holds thumbnail images of the object and the spectra. The database is accessed/queried using Structured Query Language (SQL). A combined redshift catalogue (6dF + literature) is provided in a separate single master catalogue.

The input catalogues that were merged to make up the master target list are also held in individual tables; Every table is interlinked via the common parameters `targetid` and `targetname`. The master target list (used to configure 6dFGS observations) forms the hub of the database.

Access to the database is through two different Hypertext Mark-up Language (HTML) entry forms. Both parse the user input and submit an SQL request to the database. For users unfamiliar with SQL, the menu driven form provides guidance in constructing a query. Both forms allow the user to select different types of output (HTML, comma separated value (CSV) or a TAR save-set of FITS files). There are online examples of different queries using either the menu or SQL form at `http://www-wfau.roe.ac.uk/6dFGS/examples.html`. More information about the database is available directly from the 6dFGS database website.

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