Maps of the Cosmos
ASP Conference Series, Vol. 216, 2005
M. Colless, L. Staveley-Smith, R. Stathakis

"Cosmic Windows" Sky Surveys

J. J. Condon,[1] W. D. Cotton,[1] Q. F. Yin,[1] T. M. Heckman,[2]
C. J. Lonsdale,[3] H. E. Smith,[3] C. D. Martin,[4] D. Schiminovich,[4]
S. J. Oliver,[5] and H. J. A. Röttgering[6]

[1]*National Radio Astronomy Observatory, 520 Edgemont Road, Charlottesville, VA 22903, USA*
[2]*Johns Hopkins University, Department of Physics & Astronomy, Homewood Campus, Baltimore, MD 21218, USA*
[3]*Infrared Processing and Analysis Center, California Institute of Technology, 100-22, Pasadena, CA 91125, USA*
[4]*California Institute of Technology, MS 405-47, Downs Laboratory, Pasadena, CA 91125, USA*
[5]*University of Sussex, Falmer, GB Brighton BN1 9QH, UK*
[6]*Leiden University, Box 9513, NL 2300 RA Leiden, The Netherlands*

Abstract. Far-infrared (FIR), ultraviolet (UV), and soft X-ray observations are easily degraded by dust and gas between the source and the telescope. They must be made from space, where they are still affected by the interstellar medium (ISM) of our Galaxy. Fortunately the ISM is quite patchy, with several "cosmic windows" covering ~ 100 deg^2 of sky having exceptionally low interstellar extinction and cirrus emission. Since the universe is nearly isotropic, these windows contain representative samples of cosmologically distant sources and will be the targets of deep multiwavelength studies including SWIRE, GALEX/DIS, and XMM-LSS. Overlapping optical and radio surveys provide essential source identifications, redshifts, morphologies, and continuum spectra. The prototype VLA survey (see `http://www.cv.nrao.edu/sirtf_fls/`) covers the 5 deg^2 SIRTF First-Look Survey (FLS) and is being used to identify the expected FIR sources in advance. Most will be star-forming galaxies obeying the very tight far-infrared/radio correlation and thus continuum radio sources stronger than $S \approx 100\,\mu$Jy at 1.4 GHz. Proposed VLA surveys covering the remaining "cosmic windows" will be useful for studying the evolution of obscured AGNs, clusters, and other uncommon objects.

1. Cosmic Windows

Truly multiwavelength observations of galaxies at cosmological distances must include the FIR, UV, and soft X-ray bands which are strongly affected by either Galactic extinction or foreground emission. The amount of intervening matter along a line-of-sight is usually measured by the neutral Hydrogen column density $N_{\rm H}$ (Dickey & Lockman 1990) or by the the $\lambda = 100\,\mu$m cirrus brightness (Schlegel et al. 1998). Figure 1 shows that $N_{\rm H}$, averaged over $1^\circ \times 1^\circ$ squares, varies by a factor of 100. Regions with $N_{\rm H} < 10^{20}$ cm^{-2} have column densities not more than twice the lowest observed column density, and these

https://doi.org/10.1017/S0074180900196792 Published online by Cambridge University Press

low-extinction "cosmic windows" cover $< 1\%$ of the sky. They also produce the darkest $100\,\mu$m foregrounds, ≈ 0.5 MJy sr^{-1}.

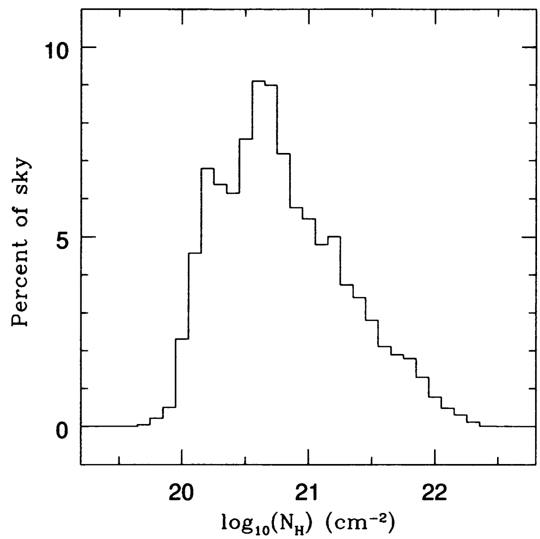

Figure 1. The H I column densities $N_{\rm H}$ averaged over squares 1° on a side (Dickey & Lockman 1990).

Fortunately, the "cosmological principle" asserts that the distribution on the sky of distant galaxies is sufficiently isotropic that fair samples can be drawn from surveys covering only the best of these cosmic windows. The most striking observational evidence for this assertion is presented in Figure 2, showing in equal-area polar projections the positions of NVSS (Condon et al. 1998) radio sources north of $\delta = -40°$ having $S > 100$ mJy at 1.4 GHz (top) and those with $\delta > +75°$ and $S > 2.5$ mJy (bottom). The Galaxy is barely discernable at the left edge of the upper plot. The rest of the sky is dominated by extragalactic sources with median redshift $\langle z \rangle \sim 1$.

Three space observatories are now making large-area surveys through these cosmic windows with enough sensitivity to detect thousands of galaxies and AGNs at cosmological distances. Near the end of 2003 the SIRTF First-Look Survey (FLS; see `http://sirtf.caltech.edu/SSC/fls/`) will map 5 deg^2 of the darkest infrared sky in the SIRTF northern constant-viewing zone at levels $100\times$ fainter than IRAS reached. The SIRTF Wide-Area Infrared Extragalactic survey (SWIRE; Lonsdale et al. 2003; `http://www.ipac.caltech.edu/SWIRE/`) will image about 70 deg^2 in seven cosmic windows each > 5 deg^2 in size to trace the evolution of star-forming galaxies, clusters, and AGNs to $z \sim 3$. The GALEX (GALaxy Evolution eXplorer; `http://www.srl.caltech.edu/galex/`) telescope will make a Deep Imaging Survey (DIS) over ≈ 100 deg^2 to $AB \approx 25.5$ in areas overlapping SWIRE. The XMM/Newton LSS (Large-Scale Structure) X-ray survey (`http://vela.astro.ulg.ac.be/themes/spatial/xmm/LSS/`) is

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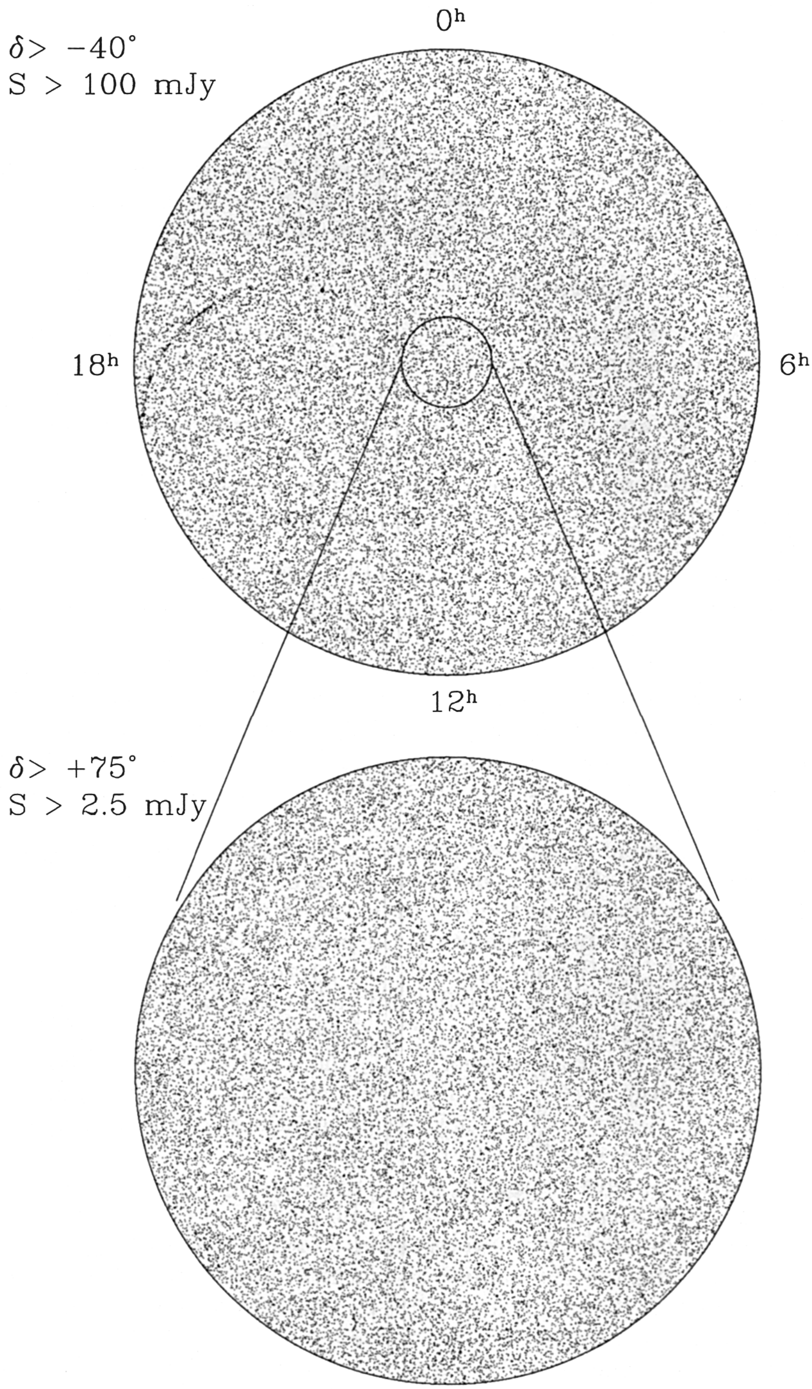

Figure 2. The radio universe is extraordinarily isotropic because most sources are cosmologically distant.

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being made in an $8^\circ \times 8^\circ$ square chosen to minimize $N_{\rm H}$ subject to the constraint of good XMM visibility.

2. Radio Surveys

Radio surveys are needed to complete the multiwavelength coverage of the cosmic windows. This section outlines some of their scientific uses and explores the main technical considerations associated with radio surveys.

2.1. Scientific Applications

Nearly all star-forming galaxies obey the very tight FIR/radio correlation and can be distinguished from radio-loud AGNs by their FIR/radio flux ratios, usually specified by the logarithmic paramater q (Helou et al. 1988) at 1.4 GHz. Its mean and rms are $\langle q \rangle \approx 2.3$ and $\sigma_q \approx 0.18$ for star-forming galaxies. Galaxies with $q < 1.8$ are > 3 times more "radio loud" and their radio emission is likely to be AGN-dominated. Also, AGNs can be recognized via their large-scale structures (jets and lobes) or high brightness temperatures, $T_{\rm b} \gg 10^5$ K at 1.4 GHz (Condon 1992).

In addition, most μJy radio sources are produced by star-forming galaxies, so flux-limited samples of FIR and radio sources have a very large overlap. The local luminosity functions at radio and FIR wavelengths (Figure 3) are indistinguishable, so either radio or FIR data can be used to obtain extinction-free estimates of the mean star-formation-rate density SFR (e.g., $M_\odot$ yr^{-1} Mpc^{-3}) in the universe today (Condon et al. 2002). Statistical uncertainties in the current SFR can be reduced only by maximizing the volume sampled within lookback times $\ll H_0^{-1}$; that is, via surveys covering a large fraction of the celestial sphere.

The deepest radio surveys covering very small areas of sky (< 1 deg^2) have reached levels below the FIR confusion limits of SIRTF for galaxies obeying the FIR/radio correlation, so the μJy radio source counts are uniquely sensitive indicators of obscured star-formation in the past. The evolutionary source-count model of Condon (1984) constrained by the approximate redshift distributions of faint radio sources can be combined to yield extinction-free *radio* estimates for the evolution of star formation out to redshifts $z \sim 2$ (Figure 4). The main weaknesses of this result are caused by (1) the small numbers of radio sources in existing ultradeep surveys, (2) possible contamination of the radio sample by unrecognized AGNs, and (3) incomplete identifications and very uncertain redshift distributions, especially at higher redshifts.

Deep radio surveys combined with SIRTF surveys can be used to make photometric redshift estimates (Yun & Carilli 2002) and explore the FIR/radio correlation at high redshifts. However, inverse-Compton scattering off the CMB at large z may deplete the supply of synchrotron-emitting electrons in low-luminosity galaxies whose magnetic energy densities do not exceed the CMB energy density, which is equivalent to $\approx 3\,\mu{\rm G}(1+z)^2$.

AGNs are uncommon in FIR surveys, accounting for only $\sim 2\%$ of the FIR sources in the local universe (Condon et al. 1995) and $< 20\%$ of the $\lambda = 15\,\mu$m background (Fadda et al. 2002), so the sky coverage of the SIRTF FLS and SWIRE surveys are needed for constructing large samples of obscured AGNs.

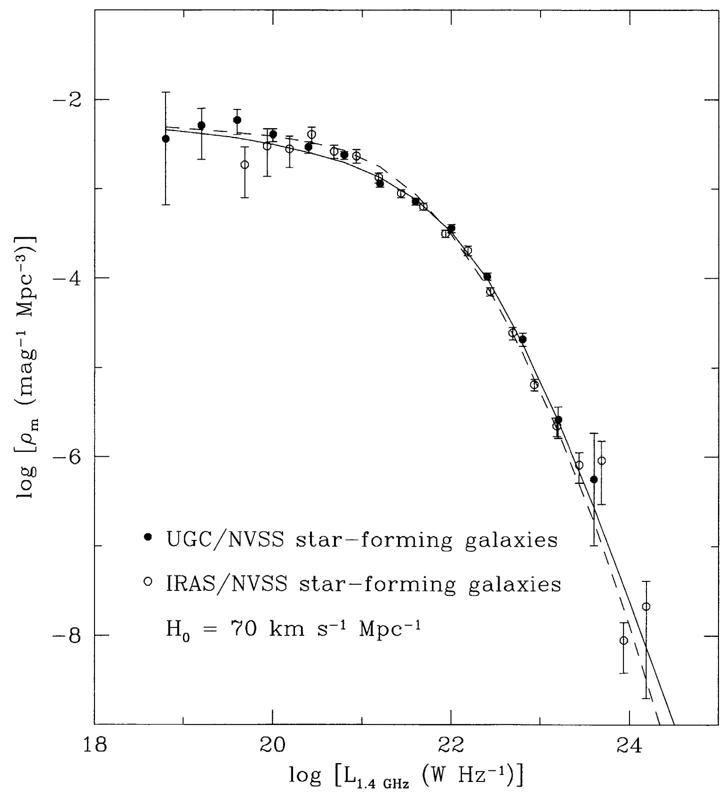

Figure 3. The 1.4 GHz local luminosity function of star-forming galaxies (data points and solid curve) is indistinguishable from the FIR local luminosity function (dashed curve) after rescaling to 1.4 GHz by the FIR/radio correlation (Condon et al. 2002).

The VLA survey covering the FLS area (Condon et al. 2003) can easily detect all AGNs sufficiently radio loud ($q < 1.8$) to be distinguishable from starbursts, and a 1.4 GHz survey with a detection limit $S_m = 5\sigma \approx 200\,\mu$Jy could find all AGNs with $q < 1.8$ that will be found in the large SWIRE survey area. Unbiased samples of AGNs selected at FIR wavelengths are useful for testing "unification" models involving dust extinction or relativistic beaming.

2.2. The "Wedding Cake" Survey Strategy

The "wedding cake" survey strategy of making several radio surveys covering different solid angles Ω with different point-source detection limits S_m and angular resolutions θ can be justified as follows. For a given amount of telescope time T, there is a tradeoff between solid-angle coverage Ω and integration time τ: $T \propto \Omega\tau$. In the μJy flux-density range, the radio source counts can be approximated by $N(> S) \propto S^{-1}$. The sensitivity limit $S_m \propto \tau^{-1/2}$, so the total number of radio sources detectable in time T obeys $N \propto \Omega^{1/2} \propto \tau^{-1/2} \propto S_m$. Thus large but insensitive surveys are the most productive for finding sources.

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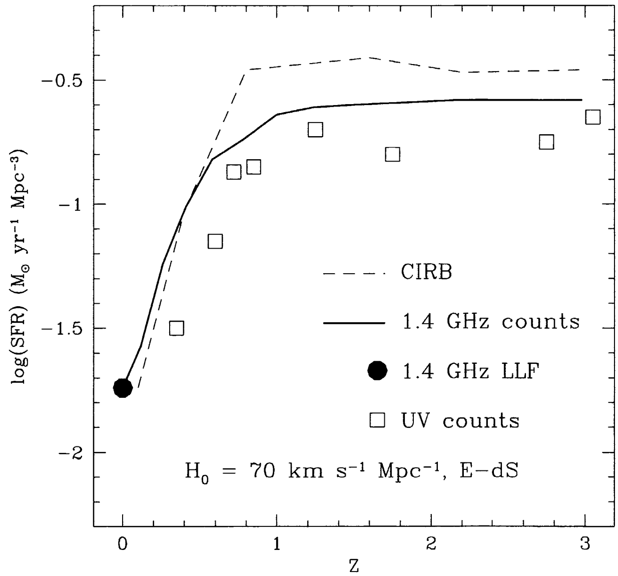

Figure 4. The star-formation rate per unit comoving volume estimated from radio data. The filled circle at $z \approx 0$ was derived from the local radio luminosity function (Figure 3), and the solid curve from an evolutionary model for the counts and redshift distributions of μJy radio sources (Condon 1984). Open squares show extinction-corrected UV data (Steidel et al. 1999) and the dashed curve indicates the Chary & Elbaz (2001) model for the FIR background, corrected to $H_0 = 70$ km s^{-1} Mpc^{-1}.

Small, sensitive surveys are relatively expensive and should be made only as needed to match particular scientific requirements.

The angular resolution θ is also selectable for VLA surveys ($\theta \approx 45''$, $15''$, $5''$, and $1''.5$ in the D, C, B, and A configurations, respectively, at 1.4 GHz). The minimum detectable surface brightness (in Jy beam^{-1} or K) scales as $T_{\rm b} \propto \theta^{-2}$, so low-resolution surveys are needed to detect extended sources in nearby low-luminosity galaxies. Even high-redshift sources of galaxian size may be missed if $\theta \lesssim 1''.5$. High resolution is most desirable for measuring the accurate positions needed to identify faint radio sources with distant galaxies. The rms position uncertainty in each coordinate caused by noise is $\sigma \approx \theta\sigma_{\rm n}/(2S)$, where $\sigma_{\rm n}$ is the rms noise. For the faintest detectable sources ($S_{\rm m} \approx 5\sigma_{\rm n}$), $\sigma \approx \theta/10$. Confusion by foreground and background extragalactic radio sources can also limit the sensitivity and position accuracy of radio surveys. Since $N(>S) \propto S^{-1}$ in the relevant flux-density range, the rms confusion scales as $\sigma_{\rm c} \propto \theta^2$. At 1.4 GHz, $\sigma_{\rm c} \sim 10\,\mu$Jy if $\theta = 15''$ but is only a negligible $\sigma_{\rm c} \sim 1\,\mu$Jy if $\theta = 5''$. Thus current B-configuration surveys are not limited in sensitivity by faint-source confusion, and the B configuration is a good compromise for many deep VLA surveys. The A configuration is better for applications in which very accurate positions take priority over completeness.

The nearly all-sky ($\Omega \approx 3.4\times10^4$ deg^2) NVSS is the bottom layer of the radio survey cake. It complements the *IRAS* FIR surveys and the GALEX all-sky UV

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survey for studying the local population of galaxies and the most luminous radio AGNs at all redshifts, but its sensitivity ($S_m \approx 2.5$ mJy) is not good enough to detect star-forming galaxies at cosmological distances. The top layer consists of a few extremely deep surveys spanning only one primary beam area ($\Omega \ll 1$ deg^2) of the VLA (e.g., the Richards et al. 1998 survey covering the HDFN). They detect very few sources, however. What is needed is the middle layer, consisting of radio surveys having intermediate sensitivity, to match the $\Omega \sim 10^2$ deg^2 sky coverage of the multiwavelength "cosmic windows" surveys described in Section 1 and to detect enough sources ($N > 10^4$) for characterizing common objects accurately and estimating the statistical properties of uncommon ones. Since the "cosmic windows" will become, in effect, the selected areas for multiwavelength studies of distant galaxies for the forseeable future, a radio survey dedicated to covering these areas well will have long-term value and must eventually be made.

2.3. VLA "Cosmic Windows" Sky Surveys

The prototype of VLA "cosmic windows" sky surveys is the recently completed VLA survey (Condon et al. 2003) covering the SIRTF FLS area centered on J2000 $\alpha = 17^{\rm h}\,18^{\rm m}$, $\delta = +59^\circ\,30'$. The detection limit ($S_m = 5\sigma_n \approx 115\,\mu$Jy at 1.4 GHz) is comparable with the expected SIRTF limits at $\lambda = 70\,\mu$m and $\lambda = 160\,\mu$m for galaxies obeying the FIR/radio correlation. A total $T = 240$ hours of observing time was needed to cover $\Omega \approx 5$ deg^2 with nearly uniform sensitivity. The B configuration was used to yield $\theta = 5''$ resolution, higher than the $\theta \approx 20''$ and $\theta \approx 47''$ values expected at 70 and 160 μm, respectively. This resolution nearly eliminates confusion ($\sigma_c \approx 1\,\mu$Jy) and gives the $\sigma \lesssim 0''\!.5$ position uncertainties essential for reliable optical identifications. Most of the $N \gtrsim 3000$ unresolved radio sources will found probably obey the FIR/radio correlation, and many of the radio-loud AGNs are immediately recognizable by their extended radio morphologies. The VLA survey is an effective pre-launch finding survey that should select most of the galaxies that will appear in the FIR images while rejecting the millions of galaxies brighter than $R \approx 25.5$ that will not. Optical identifications and follow-up spectroscopic observations are in progress. The FLS should provide a good census of star-forming galaxies and trace SFR up to $z \lesssim 1$.

The full 100 deg^2 area covered by the remaining cosmic windows is too large for the VLA to survey in the near future with the sensitivity needed to match SWIRE for detecting star-forming galaxies. However, it is not impractical to survey most of the cosmic windows with the VLA B-configuration to an $S_m = 5\sigma_n \approx 200\,\mu$Jy detection limit at 1.4 GHz. Such a survey would detect $N > 2 \times 10^4$ sources. These would include a significant fraction of the star-forming galaxies detectable by SWIRE, plus all SWIRE AGNs sufficiently radio-loud to be distinguishable from star-forming galaxies. Such a large area of sky must be covered to yield statistically useful numbers of AGNs for comparison with both the dusty SWIRE AGNs and the UV QSOs that will be found by the GALEX DIS. The cosmic windows also include a number of galaxy clusters. The proposed VLA surveys can be used to relate the numbers and properties of starburst galaxies, radio galaxies, and quasars to their environments in massive clusters.

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Acknowledgments. The National Radio Astronomy Observatory is a facility of the National Science Foundation, operated under a cooperative agreement by Associated Universities, Inc.

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